DOE/EIA-M070

MODEL DOCUMENTATION REPORT: TRANSPORTATION SECTOR MODEL OF THE NATIONAL ENERGY MODELING SYSTEM

March 1994

Office of Integrated Analysis and Forecasting
Energy Information Administration
US Department of Energy
Washington, DC

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TABLE OF CONTENTS

INTRODUCTION 1
- Statement of Purpose 1
- Model Summary 1
- Model Structure 2
- Archival Citation 5
- Report Organization 5

MODEL PURPOSE AND SCOPE 7
- Objectives 7
- Model Overview 7
- Input and Output 8

MODEL RATIONALE AND STRUCTURE 13
- 3A. Light Duty Vehicle Module 15
  - Fuel Economy Model 15
  - Regional Sales Model 34
  - AFV Model 40
- 3B. LDV Stock Module 59
  - LDV Stock Accounting Model 59
  - VMT Model 66
- 3C. LDV Fleet Module 79
- 3D. Air Travel Module 91
  - Air Travel Demand Model 91
  - Aircraft Fleet Efficiency Model 99
- 3E. Freight Transport Module 113
  - Highway Freight Model 116
  - Rail Freight Model 118
  - Waterborne Freight Model 120
- 3F. Miscellaneous Energy Use Module 127
  - Military Demand Model 129
  - Mass Transit Demand Model 129
  - Recreational Boating Demand Model 131
  - Lubricant Demand Model 131
- 3G. Vehicle Emissions Module 137

TABLE OF CONTENTS (CONT.)

4. MAJOR ASSUMPTIONS 139
Overview 139
Inputs From NEMS Macro Model 139
Light-Duty Vehicle Module 140
Light Duty Vehicle Stock Module 143
Light Duty Vehicle Fleet Module 144
Air Travel Module 146
Freight Transport Module 148
Emissions Module 150

LIST OF FIGURES

Figure 2-1. NEMS and the NEMS Transportation Sector Model 11
Figure 3A-1. Fuel Economy Model 20
Figure 3A-2. Regional Sales Model 35
Figure 3A-3. Alternative Vehicle Model 47
Figure 3A-4. Fuel Economy Model 1: Economic Market Share Calculation 52
Figure 3A-5. Fuel Economy Model 2: Engineering Notes 53
Figure 3A-6. Fuel Economy Model 3: Weight and Horsepower Calculations 54
Figure 3A-7. Fuel Economy Model 4: CAFE Calculations 55
Figure 3A-8: Alternative Fuel Vehicle Model Stage 3 56
Figure 3A-9: Alternative Fuel Vehicle Model Stage 2 57
Figure 3A-10: Alternative Fuel Vehicle Model Stage 1 58
Figure 3B-1. Light Duty Vehicle Stock Module 60
Figure 3B-2. LDV Stock Module 1: Process New Additions to LDV Stock 75
Figure 3B-3. LDV Stock Module 2: Determine Characteristics of Current LDV Stock 76
Figure 3B-4. LDV Stock Module 3: Vehicle Miles Traveled Model 77
Figure 3C-1. Light Duty Vehicle Fleet Module 80
Figure 3C-2: LDV Fleet Module 1: Process New Fleet Acquisitions 87
Figure 3C-3. LDV Fleet Module 2: Determine Characteristics of Existing Fleets 88
Figure 3C-4. LDV Fleet Module 3: Determine Fleet Fuel Economy and Consumption 89
Figure 3D-1. Air Travel Module 96
Figure 3D-2. Air Travel Demand Model 1: Seat-Mile Demand Estimation 108
Figure 3D-3. Air Travel Demand Model 2: Air Freight Demand Estimation 109
Figure 3D-4. Aircraft Fleet Efficiency Model 1: Process Changes to Existing Fleet 110
Figure 3D-5. Aircraft Fleet Efficiency Model 2: Process New Stock and Calculate Fuel Demand 111
Figure 3E-1. Freight Transport Module 115
Figure 3E-2. Highway Freight Model 123
Figure 3E-3. Rail Freight Model 124
Figure 3E-4. Waterborne Freight Model 125
Figure 3F-1. Miscellaneous Energy Demand Module 128
Figure 3F-2. Military Demand Model 133
Figure 3F-3. Mass Transit Demand Model 134
Figure 3F-4. Recreational Boating Demand Model 135
Figure 3F-5. Lubricant Demand Model 136
Figure 3G-1. Vehicle Emissions Module 138

LIST OF TABLES

Table 2-1. Inputs to TRAN from Other NEMS Models 9
Table 4-1. Macroeconomic Inputs to the Transportation Model 139
Table 4-2. Car and Light Truck Fuel Economy Degradation Factors 141
Table 4-3. Alternative-Fuel Vehicle Attributes For Three-Stage Logit Model 142
Table 4-4. California Low Emission Vehicle Program Sales Mandates 143
Table 4-5. Commercial Fleet Size Class Shares By Fleet and Vehicle Type 145
Table 4-6. EPACT Alternative-Fuel Vehicle Fleet Sale Estimates 146
Table 4-7. Constant Available Seat-Miles Assumptions By Aircraft Type 147
Table 4-8. Future New Aircraft Technology Improvement List 149
Table 4-9. Distribution of Rail Fuel Consumption By Fuel Type 151

NEMS TRANSPORTATION SECTOR MODEL

1. INTRODUCTION

Statement of Purpose

This report documents the objectives, analytical approach and development of the National Energy Modeling System (NEMS) Transportation Model (TRAN). The report catalogues and describes the model assumptions, computational methodology, parameter estimation techniques, model source code, and forecast results generated by the model.

This document serves three purposes. First, it is a reference document providing a detailed description of TRAN for model analysts, users, and the public. Second, this report meets the legal requirements of the Energy Information Administration (EIA) to provide adequate documentation in support of its statistical and forecast reports *(Public Law 93-275, § 57(b)(1))*. Third, it permits continuity in model development by providing documentation from which energy analysts can undertake model enhancements, data updates, and parameter refinements.

Model Summary

The NEMS Transportation Model comprises a series of semi-independent models which address different aspects of the transportation sector. The primary purpose of this model is to provide mid-term forecasts of transportation energy demand by fuel type including, but not limited to, motor gasoline, distillate, jet fuel, and alternative fuels (such as CNG) not commonly associated with transportation. The current NEMS forecast horizon extends to the year 2010 and uses 1990 as the base year. Forecasts are generated through the separate consideration of energy consumption within the various modes of transport, including: private and fleet light-duty vehicles; aircraft; marine, rail, and truck freight; and various modes with minor overall impacts, such as mass transit and recreational boating. This approach is useful in assessing the impacts of policy initiatives, legislative mandates which affect individual modes of travel, and technological developments.

The model also provides forecasts of selected intermediate values which are generated in order

to determine energy consumption. These elements include estimates of passenger travel demand by automobile, air, or mass transit; estimates of the efficiency with which that demand is met; projections of vehicle stocks and the penetration of new technologies; and estimates of the demand for freight transport which are linked to forecasts of industrial output. Following the estimation of energy demand, TRAN produces forecasts of vehicular emissions of the following airborne pollutants by source: oxides of sulfur, oxides of nitrogen, total carbon, carbon dioxide, carbon monoxide, and volatile organic compounds.

Model Structure

The transportation sector encompasses a variety of vehicular modes which, in general, bear little physical resemblance to each other, save for their intended purpose of conveying passengers or freight. Consequently, these modes are addressed in separate modules whose interrelationship is tenuous, at best. Transportation sector energy consumption is the sum of energy consumption forecasts generated within each of these modules. Each module, in turn, may comprise more than one submodel, consistent with the methodological requirements of the sector, and commensurate with the relative impact the sector has on overall transportation demand. The NEMS Transportation Model consists of the following seven modules: Light-Duty Vehicle, Light Duty Stock, Light Duty Fleet, Air Travel, Freight Transport, Miscellaneous Transport, and Emissions. The components of these modules are briefly described in turn below.

Light-Duty Vehicle (LDV) Module

The LDV Module is the most extensive of the modules in TRAN, owing to the overwhelming contribution of automobile and light-truck use to total transportation energy demand. Forecasts of stocks and efficiencies of cars and light trucks are generated, disaggregated by vehicle size class, vintage, and engine technology, using the following submodels.

Fuel Economy Model (FEM)

The Fuel Economy Model uses estimates of future fuel prices, economic conditions, and the impact of legislative mandates to forecast the economic market share of numerous automotive technologies within seven vehicle size classes, and the consequent impact on stock fuel efficiency of new vehicles. The results are subsequently used as inputs to other components of the Transportation Model.

Regional Sales Model (RSM)

The Regional Sales Model is a simple accounting mechanism which uses exogenous estimates of new car and light truck sales, and the results of the FEM to produce estimates of regional sales and characteristics of light duty vehicles, which are then passed to the Light Duty Stock Model.

Alternative Fuel Vehicle (AFV) Model

The Alternative Fuel Vehicle Model uses estimates of new car fuel efficiency, obtained from the FEM, and fuel price estimates generated by NEMS to generate market shares of each considered technology, as well as the overall market penetration of alternative fuel vehicles. This model is useful both to assess the penetration of AFV's and to allow analysis of policies that might impact this penetration.

Light-Duty Vehicle Stock Module

LDV Stock Accounting Model

The LDV Stock Accounting Model takes sales and efficiency estimates for new cars and light trucks from the LDV and LDV Fleet Modules, determines the number of retirements of older vehicles and additions of fleet vehicles, and returns estimates of the number and characteristics of surviving vehicles.

Vehicle-Miles Traveled (VMT) Model

The VMT Model is the travel demand component of the LDV Stock Module which uses NEMS estimates of fuel price and personal income, along with population projections, to generate a forecast of the demand for personal travel. This is subsequently combined with forecasts of automotive stock efficiency to estimate fuel consumption by the existing stock of light duty vehicles.

Light-Duty Vehicle Fleet Module

The Light-Duty Vehicle Fleet Module generates estimates of the stock of cars and light trucks used in business, government, and utility fleets. The model also estimates travel demand, fuel efficiency, and energy consumption by these fleet vehicles prior to their transition to the private sector at predetermined vintages.

Air Travel Module

The air travel component of the NEMS Transportation Model comprises two separate submodels: the Air Travel Demand Model and the Aircraft Fleet Efficiency Model. These models use NEMS forecasts of fuel price, macroeconomic activity, and population growth, as well as assumptions about aircraft retirement rates and technological improvements to generate forecasts of passenger and freight travel demand and the consequent fuel consumption.

Air Travel Demand Model

The Air Travel Demand Model produces forecasts of passenger travel demand, expressed in revenue passenger-miles (RPM), and air freight demand, measured in revenue-toN miles (RTM). These are combined into a single demand for available seat-miles (ASM), and passed to the Aircraft Fleet Efficiency Model, which adjusts aircraft stocks in order to meet that demand.

Aircraft Fleet Efficiency Model (AFEM)

The Aircraft Fleet Efficiency Model is a structured accounting mechanism which, subject to user-specified parameters, provides estimates of the number of narrow- and wide-body aircraft required to meet the demand generated in the preceding model. This model also estimates aircraft fleet efficiency using a weighted average of the characteristics of surviving aircraft and those acquired to meet demand.

Freight Transport Module

The Freight Transport Module uses NEMS forecasts of real fuel prices, trade indices, and selected industries' output from the Macroeconomic Model to estimate travel demand and energy consumption in each of three primary freight modes: truck, rail, and marine. This component also provides estimates of modal efficiency growth, driven by assumptions about systemic improvements and modulated by fuel price forecasts.

Miscellaneous Energy Use Module

The Miscellaneous Energy Use Module addresses transportation-related energy demands which can not readily be allocated to any of the preceding modules. These include: military fuel consumption, mass transit, recreational boating, and automotive lubricants.

Vehicle Emissions Module

The Vehicle Emissions Module receives estimates of energy consumption, by mode, from all of the preceding modules, and calculates vehicular emissions based on both the mix of vehicle technologies utilized over time, and the age distribution of these vehicles.

Model Archival Citation

Archived as part of the NEMS production runs for the *Annual Energy Outlook 1994*.

Report Organization

Chapter 2 of this report discusses the purpose of the Transportation Model, detailing its objectives, primary input and output quantities, and the relationship of TRAN to the other modules of the NEMS system. In Chapter 3, each of the constituent modules is addressed in detail, describing the rationale behind the module's design. Where appropriate, alternative methodological approaches to the issues raised in each module are presented, thus permitting a ready comparison with the approaches chosen for NEMS. Each module's structure is then presented in detail, illustrating model flows and key computations. Chapter 4 provides an overview of the principal assumptions employed in constructing the Transportation Model.

The Appendices to this report provide micro level detail as supporting documentation for the TRAN files currently residing on the EIA mainframe. Appendix A lists and defines the input data used to generate parameter estimates and endogenous forecasts from TRAN, along with the parameter estimates and the outputs of most relevance to the NEMS system and the model evaluation process. Appendix B contains a mathematical description of the computational algorithms used in TRAN, including model equations and variable transformations. Appendix C is a bibliography of reference materials used in the development process. Appendix D consists of a model abstract. Appendix E discusses data quality and estimation methods. Appendix F contains a number of attachments which are meant to provide insight into the historical development of the NEMS Transportation Sector Model. Finally, Appendix G comprises two reports used in the development of the Fuel Economy Model.

Volume II of this report documents technical detail on model data and equations and sensitivity analysis and scenario output in support of the documentation of model performance.

2. MODEL PURPOSE AND SCOPE

Objectives

The development of the NEMS Transportation Model has achieved four objectives. First, it provides a policy-sensitive representation of the transportation sector within NEMS. Second, it generates mid- to long-term forecasts (ten to twenty years) of transportation energy demand at the census division level in support of the development of the *Annual Energy Outlook* (AEO). Third, it increases the level of disaggregation provided in previous transportation models, and fourth, it incorporates endogenous forecasts of the effects of technological innovation and vehicle choice.

Model Overview

The Transportation Model is a loosely-knit group of submodules which are sequentially executed in a series of program calls. The flow of information between these modules is depicted in Figure 2-1. The model receives inputs from NEMS, principally in the form of fuel prices, vehicle sales, economic and demographic indicators, and estimates of defense spending. These inputs are described in greater detail in the following section.

The first module executed is the Light Duty Vehicle (LDV) Module, which addresses the characteristics of new cars and light trucks. This module comprises a series of submodels which provide estimates of new LDV fuel economy, the market shares of alternative fuel vehicles, and sales of vehicles to fleets. This information is passed to the LDV Fleet Module, a stock vintaging model which generates estimates of travel demand, fuel efficiency, and energy consumption by business, government, and utility fleets. The LDV Fleet Module subsequently passes estimates of vehicles transferred from fleet to private service to the LDV Stock Module, which also receives estimates of new LDV sales and fuel efficiency from the LDV Module. The LDV Stock Module generates driving, fuel economy, and fuel consumption estimates of the entire stock of those light duty vehicles which are not owned by fleets. Information from the LDV Stock Module is subsequently passed to the Miscellaneous Energy Use Module.

The Air Travel Module receives macroeconomic and demographic input from NEMS, including jet fuel prices, population, per capita GDP, disposable income and merchandise exports, and

subsequently uses an econometric estimation to determine the level of travel demand and a stock vintaging model to determine the size and characteristics of the aircraft fleet required to meet that demand. The output of this module also includes an estimate of the demand for jet fuel and aviation gasoline, which is subsequently passed to the Miscellaneous Energy Use Module. The Freight Transport Module uses NEMS forecasts of real fuel prices, trade indices, and selected industries' output to estimate travel demand and energy consumption in each of three primary freight modes: truck, rail, and marine. Travel and fuel demand estimates are subsequently passed to the Miscellaneous Energy Use Module.

The Miscellaneous Energy Use Module receives estimates of military expenditures from NEMS to generate military fuel demand estimates; travel demand estimates from the LDV Stock Module and fuel efficiency estimates from the Freight Transport Module are used to calculate regional fuel consumption by mass transit vehicles; estimates of disposable personal income from NEMS are used to calculate the demand for fuel used in recreational boating; and the aggregate demand for highway travel, obtained from the preceding modules is used to estimate the demand for lubricants used in transportation. Finally, the Emissions Module uses estimates of travel demand and fuel consumption from all the preceding modules to determine the production of airborne pollutants.

The Transportation Model then sends information on regional fuel consumption, travel demand, fuel economy, and emissions by transport mode and vehicle type back to NEMS, where it is integrated with the results of the economic and supply models.

Input and Output

In order to generate forecasts, the Transportation Model receives a variety of exogenous inputs from other NEMS modules. The primary source of these inputs is the Macroeconomic Model, which provides forecasts of economic and demographic indicators. Other inputs exogenous to TRAN but endogenous to NEMS include fuel prices forecasts from the various supply models. A complete listing of NEMS inputs to TRAN is provided in the table below.

A large number of data inputs exogenous to NEMS are supplied to the TRAN modules described above. These data sets remain constant throughout the forecast, and, to that extent, constitute a set of assumptions about current and future conditions. A comprehensive list of these invariant inputs, under the classification "data inputs", is provided in Table A-1 of Appendix A.

Table 2-1. Inputs to TRAN from Other NEMS Models

NEMS Macro Model: Economic and Demographic Indicators	NEMS Supply Models: Prices			
	Oil & Gas	Petroleum Marketing	Renewables	Electricity Market
• Merchandise Imports • Merchandise Exports • Gross Domestic Product (GDP) • GDP Deflator • Disposable Income • U.S. Population • U.S. Population over 16 • U.S. Population over 60 • Industrial Output by SIC Code • Defense Spending	• LPG • CNG	• Motor Gasoline • Distillate • Residual Fuel Oil • Methanol • Jet Fuel • Aviation Gasoline	• Ethanol	• Electricity

The Light Duty Vehicle Module, with its numerous submodels, requires the largest number of exogenous inputs. In the Fuel Economy Model, these inputs include the characteristics of the considered automotive technologies, such as their effects on vehicle horsepower, weight, fuel efficiency, and price. Vehicle characteristics in the AFV Model are similarly obtained, with vehicle price, range, emissions levels, and relative efficiency being read in from an external data file.

The LDV Stock Module uses vintage-dependent constants such as vehicle survival and relative driving rates, and fuel economy degradation factors to obtain estimates of stock efficiency.

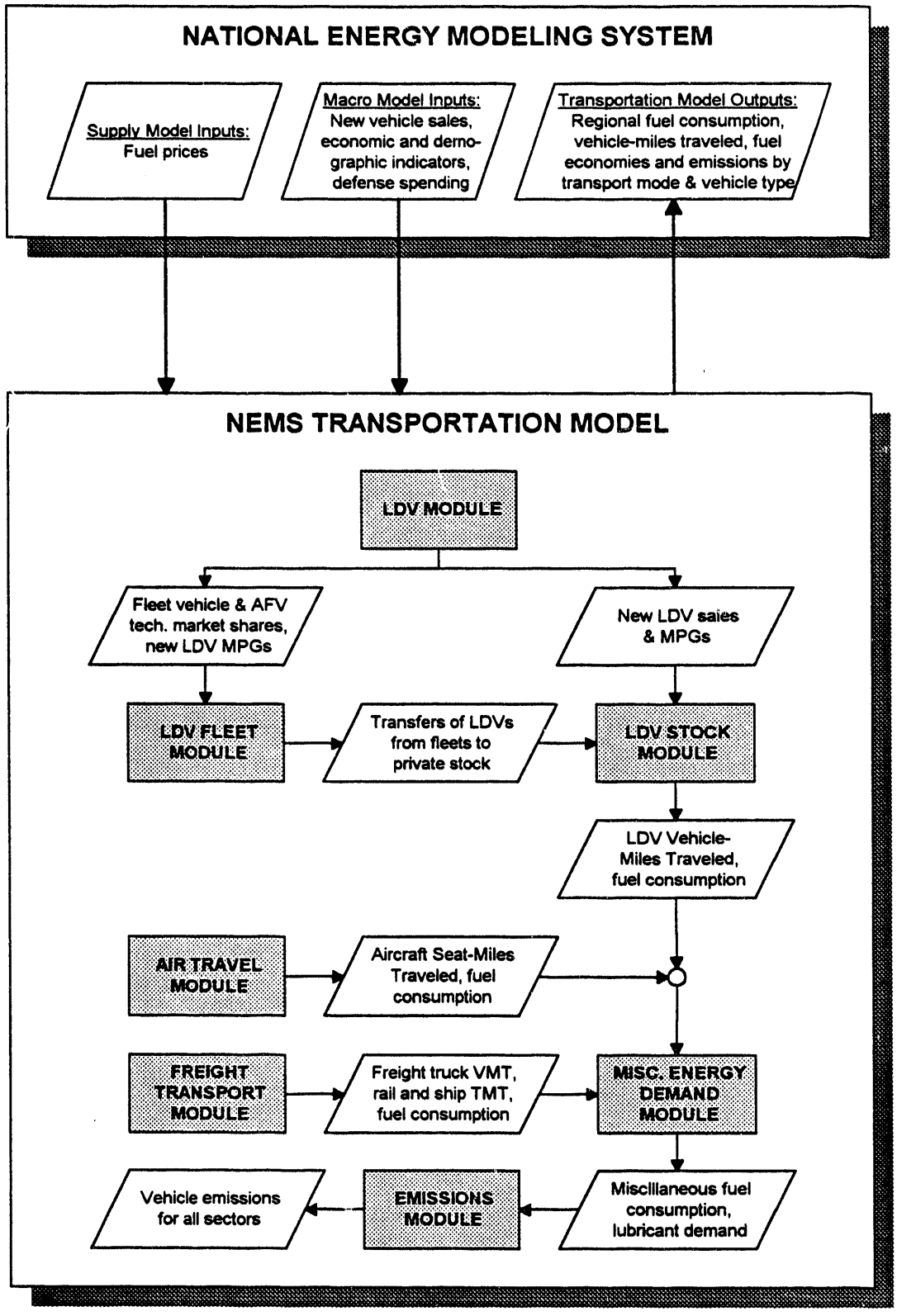
The Air Travel Module receives exogenous estimates of aircraft load factors, new technology characteristics, and aircraft specifications which determine the average number of available seat-miles each plane will supply in a year. The Freight Module receives exogenous estimates of freight intensity and modal shares. Finally, the Emissions Module is supplied a set of coefficients which associate energy use by vehicle and fuel type with the consequent emissions of each of the six airborne pollutants considered by the model.

Each submodel performs calculations at a level of disaggregation commensurate with the nature of the mode of transport, the quality of the input data and the level of detail required in the output. For example, the FEM addresses seven size classes of car and light truck, while the

Stock Module considers six separate classes, and the AFV Model only three. The Transportation Model maps the output of each submodel into variables of the appropriate dimension for use in subsequent steps. Due to the lack of a uniform stratification scheme among the various transportation sectors, the primary dimensions across which key variables vary in TRAN are discussed in the individual module descriptions in the following section.

As described previously, the Transportation Model produces forecasts of travel demand, disaggregated by census division, vehicle and fuel type; conventional and alternative vehicle technology choice; vehicle stock and efficiency; energy demand, by vehicle and fuel type; and emissions of specific airborne pollutants. Within NEMS, TRAN has an interactive relationship with the Macroeconomic Module and the various supply modules, which provide the prices of transportation-related fuels at a given level of demand. In each year of the forecast, NEMS performs several iterations in order to derive a set of fuel prices under which supply and demand converge. The reliance of each of the submodels in TRAN on these economic and price inputs is made clear with the detailed model specifications in the following section.

Figure 2-1. NEMS and the NEMS Transportation Sector Model



3. MODEL RATIONALE AND STRUCTURE

As described above, the NEMS Transportation Model is made up of an array of separate modules, each addressing different aspects of the transportation field. In order to provide a consistent and lucid presentation of TRAN, each of these modules are discussed separately; where appropriate, individual module components are separately considered. Each section describes the general theoretical approach to the issue at hand, the assumptions which were incorporated in the development of the model, the methodology employed in predecessor models, and alternative approaches which were considered.

The key computations and equations of each module are then presented, in order to provide a comprehensive overview of the Transportation Model. The equations follow the logic of the FORTRAN source code very closely to facilitate an understanding of the code and its structure. In several instances, a variable name will appear on both sides of an equation. This is a FORTRAN programming device that allows a previous calculation to be updated (for example, multiplied by a factor) and re-stored under the same variable name.

Flowcharts are provided both within the text and at the end of each section. Those embedded within the "Model Structure" portion of the explanatory text give a general overview of each Module's structure, its interactions with other Modules within TRAN, and its input requirements from other NEMS Models. Flowcharts found at the end of each section are intended to be detailed, self-contained representations of Module calculations. Thus, for the sake of clarity, origins and destinations of external information flows are not specified.

The various appendices following this section provide additional information on the model development process, including background research which contributed to the quantification of the various relationships influencing model output.

3A. Light Duty Vehicle Module

This module tracks the purchases and retirements of cars and light trucks, forecasts their fuel efficiency, and estimates the consumption of a variety of fuels, based on projections of travel demand. The LDV Module is divided into three separate sections: the Fuel Economy Model, the Regional Sales Model, and the Alternative Fuel Vehicle Model. Due to the differing methodological approaches and data requirements, each section is presented individually.

3A-1. Fuel Economy Model

The Fuel Economy Model (FEM) is a subcomponent of the Light Duty Vehicle segment of the NEMS Transportation Model. FEM produces estimates of new light duty vehicle fuel efficiency which are then used as inputs to other components of the Transportation Model.

RATIONALE

The FEM is a significant component of the Transportation Model because the demand for automotive fuel is directly affected by the efficiency with which that fuel is used. Because of the disparate characteristics of the various classes of light duty vehicle, this model addresses the commercial viability of fifty-five separate technologies within each of fourteen vehicle market classes and four corporate average fuel economy (CAFE) groups. The seven automobile market classes include five classes based on interior passenger volume, ranging from "minicompact" to "large", and classes for "sports" and "luxury" cars. The seven classes of light truck are based mainly on utility and intertia weight and include vans, pickups, utility vehicles and mini-trucks. Market classes for automobiles and light trucks are described in more detail in Appendix A, Table A-2. The four groups for which CAFE standards are set are: Domestic Cars, Import Cars, Domestic Trucks, and Import Trucks.

The fuel economy of the fleet of new vehicles can change as a result of four factors:

1) A change in technological characteristics of each vehicle
2) A change in the level of acceleration performance of vehicles
3) A change in the mix of vehicle classes sold
4) A change in vehicle safety and emission standards.

Over the last 15 years, the single factor with the largest effect on fuel economy was the changing technological characteristics of cars. Except for the period immediately following the second oil

shock of 1979, the vehicle class mix has not had a very large effect on fuel economy since the mix changes have not been large. In the last five years, rapidly increasing performance levels have had a significant impact on fuel economy.

The Fuel Economy Model developed for NEMS considers each of the first three factors when projecting fuel economy in the future. To forecast technological change, the entire fleet of new cars and light duty trucks are disaggregated into fourteen market classes (seven each for cars and light trucks) that are relatively homogenous in terms of consumer perceived attributes such as size, price and utility. Technological improvements to each of these market classes are then forecast based on the availability of new technologies to improve fuel economy, as well as their cost effectiveness. The central assumptions involved in this technological forecast are as follows:

1) All manufacturers can obtain the same benefits from a given technology, provided they have adequate lead time (i.e., no technology is proprietary to a given manufacturer in the long term).

2) Manufacturers will generally adopt technological improvements that are perceived as cost-effective to the consumer, even without any regulatory pressure. However, the term cost-effectiveness needs to be interpreted in the manufacturer's context.

These forecasts also account for manufacturer lead time and tooling constraints that limit the rate of increase in the market penetration of new technologies. Based on the technological improvements adopted, a fuel economy forecast assuming constant performance is developed for each of the market classes.

The fuel economy forecast must then be adjusted to account for changes in consumer preference for performance. The demand for increased acceleration performance for each size class is estimated based on an econometric equation relating fuel prices and personal disposable income to demand for performance or horsepower, by market class. This relationship is used to forecast the change in horsepower, which is then used to forecast the change in fuel economy through an engineering relationship that links performance and fuel economy.

Finally, the change in the mix of market classes sold is forecast as a function of fuel price and personal disposable income only and is documented in Appendix E, page E-1, of this report. The sales mix by class is used to calculate fleet fuel economy. The econometric model was derived from regression analysis of historical sales mix data over the 1978-1990 period. The model forecasts sales mix for the 7 car classes and the 7 light truck classes, while import market shares

are held at fixed values by market class based on EEA estimates.

The model also allows specification of Corporate Average Fuel Economy (CAFE) standards by year, and of differential standards for domestic and import vehicles, as well as the penalty (in dollars) per car per mile per gallon below the standard. The standards are accounted for in the forecast by incorporating the penalty into the technology cost-effectiveness calculation. Hence, if the penalty is not large, the model assumes that manufacturers will adopt fuel-saving technology as long as it is cost-effective; that is, until the point where it becomes cheaper to pay the penalty for noncompliance. Thus, the model allows companies to choose non-compliance with CAFE standards as a cost-minimizing strategy, as may occur if penalties are set at unrealistic levels relative to the difficulty of achieving the CAFE standards.

Finally, the model also accounts for all known safety and emission standard changes during the forecast period. These are generally limited to the 1990-2005 time frame, however. Emission standards and safety standards increase vehicle weight, and in some cases decrease engine efficiency. The model accounts for the 1994 Tier I emission standards as well as the 2001+ Tier II emission standards, but does *not* envisage that the California "Low Emission Vehicle" standards will be adopted nationwide. Safety standards include fuel economy penalties for air bags, side intrusion and roof crush (rollover) strength requirements that are mandatory over the next ten years. Separately, anti-skid brakes are assumed to be incorporated in all vehicles, although they are not required by law.

ALTERNATIVE SPECIFICATIONS

The methodology described is implemented in the Fuel Economy Model (FEM) which builds from the earlier Technology/Cost Segment Model (TCSM) which was developed for the Department of Energy. The FEM, however, has two changes relative to the TCSM, as detailed below:

1) The FEM forecast aggregates all manufacturers by domestic and import, while the TCSM forecasts fuel economy by manufacturer for all domestic and several select import manufacturers

2) The FEM technology data is more recently updated, and captures technologies that could be available over the next 40 years, whereas the TCSM incorporates only near term technology data.

As a result of its longer term focus, the FEM incorporates a more sophisticated technology adoption and market penetration calculation algorithm than the one incorporated in the TCSM.

The adoption algorithm accounts for real world effects when cost-ineffective technologies are introduced in luxury cars for image or for performance reasons.

The forecasts are calculated at the most disaggregate level of manufacturer type (domestic/ import), vehicle type (car/light truck) and market class. Cars and light trucks are each separated into seven market classes. Each market class represents an aggregation of vehicle models that are similar in size and price, and are perceived by consumers to offer similar attributes. The car classes are similar to the EPA size classes except for the addition of sports and luxury classes that are not defined on the basis of interior volume. In addition, the classes utilized here are based on passenger volume, not passenger and trunk volume as per EPA, which results in some hatchback models differing in classification. Truck classification is essentially identical to the EPA classification. The seven classes for cars and for light duty trucks are described in Appendix A, Table A-2. This leads to a total of 28 possible classes (7 classes x 2 vehicle types x 2 manufacturer types) but some have no vehicles, e.g., there are no domestic minicompact cars. The net result is 22 different classes which are individually forecast to 2030.

MODEL STRUCTURE

The Fuel Economy Model (FEM) uses a straightforward algorithm to forecast fuel economy by vehicle class. FEM begins with a baseline, describing the fuel economy, weight, horsepower and price for each vehicle class in 1990. In each forecast period, the model identifies technologies which are available in the current year. Each available technology is subjected to a cost effectiveness test which balances the cost of the technology against the potential fuel savings and the value of any increase in performance provided by the technology. The cost effectiveness is used to generate an economic market share for the technology.

In certain cases there are adjustments which must be made to the calculated market shares. Some of these adjustments reflect engineering limitations to what may be adopted. Other adjustments reflect external forces that require certain types of technologies; safety and emissions technologies are both in this category. All of these adjustments are referred to collectively as "Engineering Notes." There are four types of engineering notes: *Mandatory*, *Requires*, *Synergistic* and *Supersedes*. These are described in detail in the following sections.

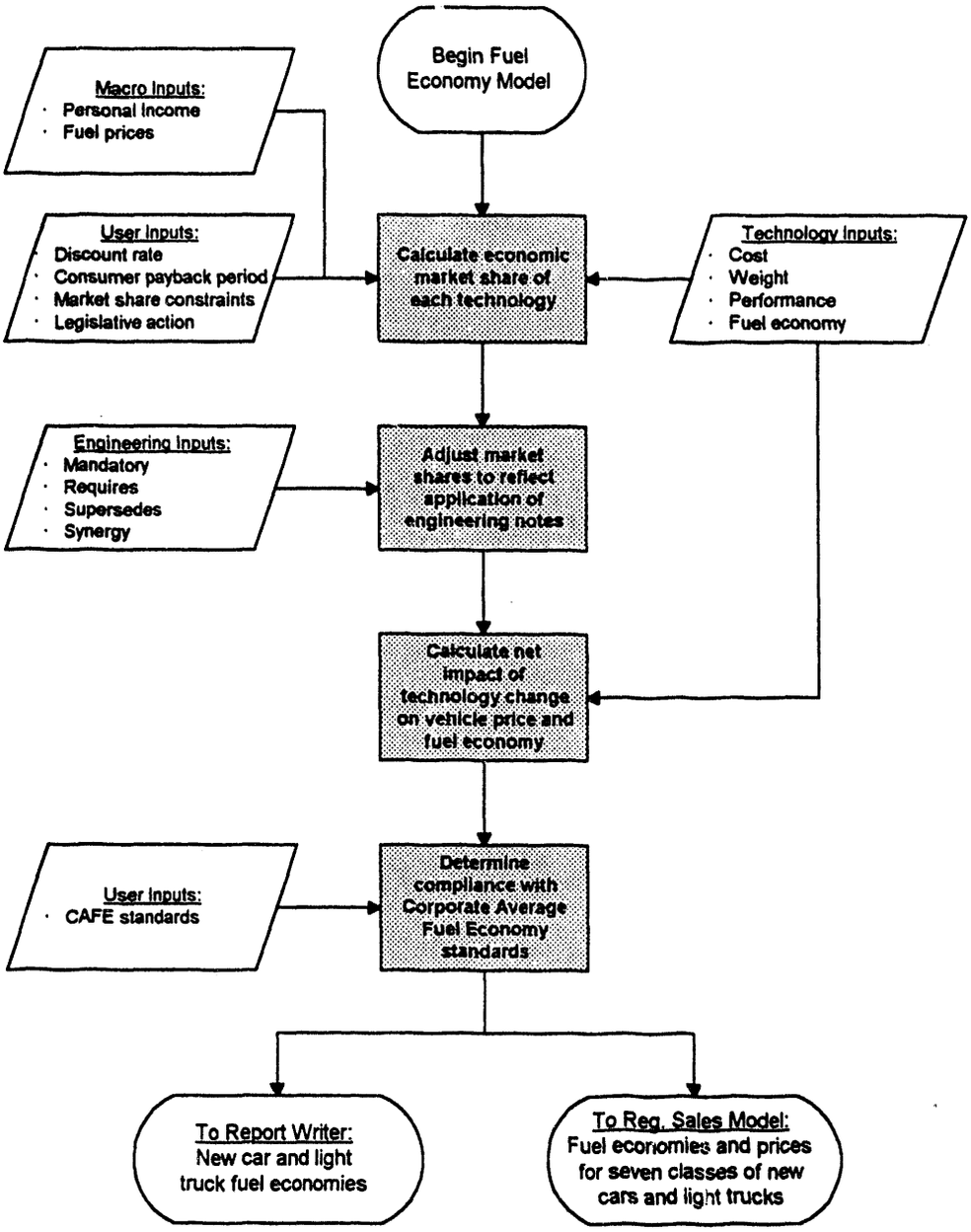
After all of the technology market shares have been determined, the baseline values for the vehicle class are updated to reflect the impact of the various technology choices on vehicle fuel economy, weight and price. Next, based on the new vehicle weight, a no-performance-change adjustment is made to horsepower. Then, based on income, fuel economy, fuel cost, and vehicle

class, a performance-change adjustment is made to horsepower. Finally, the fuel economy is adjusted to reflect the new horsepower.

Once these steps have been taken for all vehicle classes, the Corporate Average Fuel Economy (CAFE) is calculated for each of the four groups: Domestic Cars, Import Cars, Domestic Trucks and Import Trucks. Each group is classified as either passing or failing to meet the CAFE standard. When a group fails to meet the standard, penalties are assessed to all of the vehicle classes in that group, which are then reprocessed through the market share calculations. In this second pass, the technology cost effectiveness calculation is modified to include the benefit of not having to pay the fine for failing to meet CAFE. After this second pass the CAFEs are recalculated. No further action is taken to force CAFE compliance; vehicles in failing groups are assumed to simply pay the fine.

The Fuel Economy Model flowchart is presented in Figure 3A-1 below. In the interest of readability, more detailed flowcharts describing the order in which FEM calculations are made are presented at the end of Section 3A.

Figure 3A-1. Fuel Economy Model



CALCULATE TECHNOLOGY MARKET SHARES

FEM first determines the cost effective market shares of technologies for each vehicle class and then calculates the resulting Fuel Economy, Weight, Horsepower and Price through the subroutine FEMCALC. In each forecast period this function is called twice. During the first pass, technology market shares are calculated for all vehicle classes. In the second pass, the technology market shares are recalculated for vehicles in groups failing to meet the CAFE standards. During this pass, the cost effectiveness calculation is adjusted to include the regulatory cost of failing to meet CAFE[1]. If a vehicle group continues to fail to meet CAFE standards after the second pass, no further adjustments to technology market shares are made. Rather, it is assumed that the manufacturers simply pay the penalty.

For each vehicle class, FEMCALC follows these steps:

A. Calculate the economic market share for each technology

B. Apply the engineering notes to control market penetration
   - Adjust the economic market shares though application of the mandatory, supersedes and requires engineering notes
   - Adjust the fuel economy impact through application of the synergy engineering notes

C. Calculate the net impact of the change in technology market share on fuel economy, weight and price

D. Adjust horsepower based on the new fuel economy and weight

E. Readjust fuel economy based on the new horsepower, and price based on the change in horsepower

Each step is described in more detail below. Readers should note that all of the calculations in this section take place within loops by Group and Class. In the interest of legibility, these dimensions are not shown in the subscripts.

[1] See the variable REGCOST in Equation 6. During pass 1 REGCOST has a value of 0. During pass 2 it is set to REG$COST, which is a user input.

A: *Calculate the economic market share for each technology*

The cost effective market share calculation for each technology is based on the cost of the technology, the present value of the expected fuel savings and the perceived value of performance. These are addressed in turn below.

Fuel Savings Value

The "expected" price of fuel is based on the rate of change of fuel prices over a two year period prior to the year when the technology adoption decision is made. The time decision to introduce a particular technology is made at least three years before actual introduction in the marketplace, and is based on the expected fuel prices at the time of introduction rather than actual fuel prices. The expected present value of fuel savings is dependant on the "expected" price of fuel, how long the purchaser is willing to wait to recover the initial investment (the payback period); and the distance driven over the period. This estimation involves the following three steps:

1) Calculate the fuel cost slope (PSLOPE), used to extrapolate linearly the expected fuel cost over the desired payback period:

$$\mathbf{PSLOPE} = \frac{\mathbf{MAX}\ (0, \mathbf{FUELCOST}_{YEAR-3} - \mathbf{FUELCOST}_{YEAR-5})}{2} \qquad (1)$$

2) Calculate the expected fuel price (PRICE$EX) in year i (where i goes from 1 to PAYBACK):

$$\mathbf{PRICE\$EX}_i = \mathbf{PSLOPE} * (i+2) + \mathbf{FUELCOST}_{YEAR-3} \qquad (2)$$

3) Calculate the expected present value of fuel savings (FUELSAVE) over the payback period:

$$\mathbf{FUELSAVE}_{itc} = \sum_{i=1}^{PAYBACK} \mathbf{VMT}_i * \left(\frac{1}{\mathbf{FE}_{itc,YEAR-1}} - \frac{1}{(1 + \mathbf{DEL\$FE}_{itc} * \mathbf{FE}_{itc,YEAR-1})} \right) * \mathbf{PRICE\$EX}_i * (1 + \mathbf{DISCOUNT})^{-i} \qquad (3)$$

where:

VMT = Annual vehicle-miles traveled
itc = The index representing the technology under consideration
FE = The fuel economy of technology *itc*
DEL$FE = The fractional change in fuel economy associated with technology *itc*
PAYBACK = The user-specified payback period
DISCOUNT = The user-specified discount rate

Technology Cost

Technology cost has both absolute and weight dependant components. The absolute component is a fixed dollar cost for installing a particular technology on a vehicle. Most technologies are in this category. The weight dependant component is associated with the material substitution technologies. In these technologies a heavy material is replaced with a lighter one. The technology cost is a function of the amount of material, which is in turn a function of how heavy the vehicle was to begin with. The technology cost equation includes both components, although in practice one or the other term is always zero:

$$\mathbf{TECHCOST_{itc} = DEL\$COSTABS_{itc} - (DEL\$COSTWGT_{itc} * DEL\$WGTWGT_{itc} * WEIGHT_{BASEYR})} \quad (4)$$

where:

TECHCOST = The cost per vehicle of technology *itc*
DEL$COSTWGT = The weight-based change in cost ($/lb)
DEL$WGTWGT = The fractional change in weight associated with technology *itc*
WEIGHT = The original vehicle weight

Performance Value

Although there are a number of tecnological factors which affect the perceived "performance" of a vehicle, in the interests of clarity and simplicity it was decided to use the vehicle's horsepower as a proxy for the general category of performance. An increase in horsepower is assumed to reduce the fuel economy based on the relationship given in Equation 21. The perceived value of performance is also a factor in the cost effectiveness calculation. The value of performance for a given technology is positively correlated with both income and vehicle fuel economy and negatively correlated with fuel prices. In addition, purchasers of sports and luxury vehicles tend to place a higher value on performance:

$$\mathbf{VAL\$PERF_{itc} = VALUEPERF_{itc} * \frac{INCOME_{YEAR}}{INCOME_{YEAR-1}} * \frac{FE_{YEAR-1} * (1 + DEL\$FE_{itc})}{FE_{YEAR-1}} * \frac{FUELCOST_{YEAR-1}}{PRICE\$EX_{1}} * DEL\$HP_{itc}} \quad (5)$$

where:

VAL$PERF = The dollar value of performance of technology *itc*
VALUEPERF = The value associated with an incremental change in performance
FE = Vehicle's fuel economy
DEL$FE = The fractional change in fuel economy of technology *itc*
DEL$HP = The fractional change in horsepower of technology *itc*
FUELCOST = The actual price of fuel (in the previous year)

Economic Market Share

The market share of the considered technology is determined by first evaluating the cost effectiveness of technology *itc* as a function of the values described above:

$$\mathbf{COSTEFFECT}_{itc} = \frac{\mathbf{FUELSAVE}_{itc} - \mathbf{TECHCOST}_{itc} + \mathbf{VAL\$PERF}_{itc} + (\mathbf{REGCOST} * \mathbf{FE}_{YEAR-1} * \mathbf{DEL\$FE}_{itc})}{\mathbf{ABS}\,(\mathbf{TECHCOST}_{itc})} \qquad \textbf{(6)}$$

where:

COSTEFFECT = A unitless measure of cost effectiveness

REGCOST = A factor representing regulatory pressure to increase fuel economy, in $ per MPG

and:

$$\mathbf{ACTUAL\$MKT}_{itc} = \mathbf{MMAX}_{itc} * \mathbf{PMAX}_{itc} * \left(1 + e^{-2 \cdot \mathbf{COSTEFFECT}_{itc}}\right)^{-1} \qquad \textbf{(7)}$$

where:

ACTUAL$MKT = The economic share, prior to consideration of engineering or regulatory constraints.

MMAX = The maximum market share for technology *itc*

PMAX = The institutional maximum market share, which models tooling constraints on the part of the manufacturers, and is set in a separate subroutine. This subroutine (FUNCMAX) sets the current year maximum market share based on the previous year's share. The values are tabulated in Appendix A, Table A-3.

Market Share Overrides

Existing technologies are assumed to maintain their market shares unless forced out by later technologies. If the cost effectiveness calculation yields an economic market share which is below the market share in the previous period then the calculated value is overridden:

$$\mathbf{ACTUAL\$MKT}_{itc} = \mathbf{MAX}\,(\mathbf{MKT\$PEN}_{YEAR-1}\,,\ \mathbf{ACTUAL\$MKT}_{itc}) \qquad \textbf{(8)}$$

where:

MKT$PEN = Temporary variable which stores value of ACTUAL$MKT, calculated in Equation 7, from previous year

B: *Apply the Engineering Notes*

The engineering notes consist of a number of overrides to the economic cost effectiveness calculations done in the previous step. The first three types of notes (mandatory, supersedes and requires) directly affect the technology market share results obtained above. The fourth type of note, synergy, does not affect the market share and is applied after all other engineering notes have been applied.

Mandatory Notes

These are usually associated with safety or emissions technology which must be in place by a certain year. For example, air bags are mandatory in 1994. If the cost effectiveness calculations do not produce the mandated level of technology then those results are overridden as follows:

$$\mathbf{ACTUAL\$MKT_{itc} = MAX\left(ACTUAL\$MKT_{itc}\ ,\ MANDMKSH_{itc}\right)} \qquad \textbf{(9)}$$

where:

MANDMKSH = Market share for technology *itc* which has been mandated by legislative or regulatory action

Supersedes Notes

These are associated with newer technologies which replace older ones. For example, 5-speed automatic transmissions supersede 4-speed automatics. Once the cost effective market share for the newer technology (e.g. 5-speed automatics) has been calculated, the market share(s) of the older technology(ies) (e.g. 4-speed automatics) are reduced, if necessary, to force the total market shares for the old and new technologies to add up to 100 percent.

For example, given a group of competing technologies A, B, and C, suppose that C is the oldest technology while A is the newest. After calculating the economic market share for each technology, and applying the *mandatory* notes as described above, the following steps are then taken:

1) Add the three market shares together:

$$\mathbf{SUM\$MKT = ACTUAL\$MKT_A + ACTUAL\$MKT_B + ACTUAL\$MKT_C} \qquad \textbf{(10)}$$

2) Identify the largest maximum market share for the group of technologies:

$$MMAX = MAX(MKT\$MAX_A, MKT\$MAX_B, MKT\$MAX_C) \quad (11)$$

where:

MKT$MAX = Maximum market share of technology *itc*

3) If SUM$MKT <= MMAX, then make no adjustments.
4) If SUM$MKT > MMAX, then subtract market share from technology C until the sum of the market shares equals MMAX, or until $ACTUAL\$MKT_C = 0$.
5) If SUM$MKT is still greater than MMAX, subtract market share from technology B until the sum of the market shares equals MMAX.

Requires Notes

These notes control the adoption of technologies which require that other technologies also be present on the vehicle. For example, since Variable Valve Timing II requires the presence of an Overhead Cam, the market share for Variable Valve Timing II cannot exceed the sum of the market shares for Overhead Cam 4, 6 & 8 cylinder engines. This note is implemented as follows:

1) For a given technology *itc*, define a group of potential matching technologies, one of which must be present for *itc* to be present.
2) Sum the market shares of the matching technologies (*req*):

$$REQ\$MKT = \sum_{req}^{RQ} ACTUAL\$MKT_{req} \quad (12)$$

where:

REQ$MKT = The market share of required complementary technologies to technology *itc*.
req = Index referring to all required complementary technologies to technology *itc*.
RQ = Number of required complementary technologies to technology *itc*.

3) Compare REQ$MKT to the market share of technology *itc*: $ACTUAL\$MKT_{itc}$.
4) If $ACTUAL\$MKT_{itc}$ <= REQ$MKT, then make no change.
5) If $ACTUAL\$MKT_{itc}$ > REQ$MKT, then set $ACTUAL\$MKT_{itc}$ = REQ$MKT

It is at this point that the adjusted economic market share, $ACTUAL\$MKT_{itc}$, is assigned to the variable $MKT\$PEN_{itc,Year}$ for use in the remainder of the calculations.

Synergistic Notes

Synergistic technologies are those which, when installed simultaneously, interact to affect fuel economy. A vehicle with synergistic technologies will not experience the change in fuel economy predicted by adding the impact of each technology separately. Conceptually such interactions could yield either greater or lower fuel economy; however, in all cases observed in FEM the actual fuel economy is lower than expected. For example, Variable Valve Timing I is synergistic with 4-speed automatic transmissions. If both are present on a vehicle then the actual fuel economy improvement is 2 percent below what would be expected if the technologies were simply added together with no regard for their interaction.

Synergy adjustments are made once all other engineering notes have been applied. For each synergistic pair of technologies the fuel economy is adjusted as follows:

$$\begin{aligned} FE_{YEAR} = FE_{YEAR} &+ \left(MKT\$PEN_{itc1,YEAR} - MKT\$PEN_{itc1,YEAR-1}\right) \\ &* \left(MKT\$PEN_{itc2,YEAR} - MKT\$PEN_{itc2,YEAR-1}\right) * SYNR\$DEL_{itc1,itc2} \end{aligned} \quad (13)$$

where:

FE = Fuel economy, by size class and group, initialized to the previous year's value and subsequently modified with each iteration of the model.

itc1 = First synergistic technology

itc2 = Second synergistic technology

SYNR$DEL = The synergistic effect of the two technologies on fuel economy

C: Calculate Net Impact of Technology Change

The net impact of changes in technology market shares is first calculated for fuel economy, weight and price. Horsepower is dependant on these results and must be calculated subsequently. For a given technology *itc*, the change in market share since the last period (DELTA$MKT) is calculated as follows:

$$DELTA\$MKT_{itc} = MKT\$PEN_{itc,YEAR} - MKT\$PEN_{itc,YEAR-1} \quad (14)$$

$DELTA\$MKT_{itc}$ is used to calculate the incremental changes in fuel economy, vehicle weight, and price due to the implementation of the considered technology.

Fuel Economy

Current fuel economy for a vehicle class is calculated as the previously adjusted fuel economy plus the sum of incremental changes due to newly adopted technologies:

$$FE_{YEAR} = FE_{YEAR} + \sum_{itc=1}^{NUMTECH} FE_{YEAR-1} * DELTA\$MKT_{itc} * DEL\$FE_{itc} \quad (15)$$

where:

NUMTECH = Number of newly adopted technologies

Vehicle Weight

Current weight for a vehicle class is calculated as the current weight plus the sum of incremental changes due to newly adopted technologies. As with the technology cost equation, the weight equation has both absolute and variable components. Most technologies add a fixed number of pounds to the weight of a vehicle. With material substitution technologies the weight change depends upon how much new material is used, which is a function of the original weight of the vehicle. The weight equation includes both absolute and weight dependant terms in the summation expression. For any given technology, one term or the other will be zero.

$$WEIGHT_{YEAR} = WEIGHT_{YEAR} + \sum_{itc=1}^{NUMTECH} DELTA\$MKT_{itc} * \left[DEL\$WGTABS_{itc} + \left(WEIGHT_{BASEYR} * DEL\$WGTWGT_{itc}\right)\right] \quad (16)$$

where:

DEL$WGTABS = The change in weight (lbs) associated with technology *itc*

DEL$WGTWGT = The fractional change in vehicle weight due to technology *itc*

WEIGHT = Vehicle weight, by size class and group, initialized to the previous year's value and subsequently modified with each iteration of the model.

Vehicle Price

Current price for a vehicle class is calculated as the current price plus the sum of incremental changes due to newly adopted technologies. As with the weight equation, the price equation has both absolute and variable components. Most technologies add a fixed cost to the price of a vehicle. For the material substitution technologies, cost depends on the amount of new material used, which is in turn dependent on the original weight of the vehicle. The price equation

includes both absolute and weight dependant terms in the summation expression. For any given technology, one term or the other will be zero.

$$PRICE_{YEAR} = PRICE_{YEAR} + \sum_{itc=1}^{NUMTECH} DELTA\$MKT_{itc} * \left[DEL\$COSTABS_{itc} + (WEIGHT_{YEAR} - WEIGHT_{BASEYR}) * DEL\$COSTWGT_{itc} \right] \quad (17)$$

where:

DEL$COSTABS = The cost of technology *itc*

DEL$COSTWGT = The weight-based change in cost of technology *itc* ($/lb)

PRICE = Vehicle price, by size class and group, initialized to the previous year's value and subsequently modified with each iteration of the model.

D: Adjust Horsepower

Calculating the net impact of changes in technology share on vehicle horsepower is a two step process. First, horsepower is calculated on the basis of weight; this step assumes no change in performance. This initial estimate simply maintains the weight to horsepower ratio observed in the base year:

Unadjusted Horsepower

Assuming a constant weight/horsepower ratio:

$$HP_{YEAR} = HP_{BASEYR} * \frac{WEIGHT_{YEAR}}{WEIGHT_{BASEYR}} \quad (18)$$

where:

HP = Vehicle horsepower

WEIGHT = Vehicle weight

Adjustment Factor

The second step adjusts horsepower for changes in performance. This calculation is based on household income, vehicle price, fuel economy, fuel cost, and the perceived desire for performance (PERFFACT):

$$ADJHP = PERFFACT * \left[\left(\frac{INCOME_{YEAR}}{INCOME_{YEAR-1}} \right)^{0.8} * \left(\frac{PRICE_{YEAR-1}}{PRICE_{YEAR}} \right)^{0.8} * \left(\frac{FE_{YEAR}}{FE_{YEAR-1}} \right)^{0.2} * \left(\frac{FUELCOST_{YEAR-1}}{FUELCOST_{YEAR}} \right)^{0.2} - 1 \right] \quad (19)$$

where:

ADJHP = Vehicle horsepower adjustment factor

Note that if income, vehicle price, fuel economy and fuel cost remain the same, the expression in parentheses resolves to: (1*1*1*1 - 1) = 0. Thus, unless there is some change in the economics, there will be no change in horsepower due to a desire for more performance. In an economic status quo, the only changes in horsepower will be those required to maintain the base year weight-to-horsepower ratio calculated above.

Adjusted Horsepower

The current year horsepower is then calculated as follows:

$$HP_{YEAR} = HP_{YEAR} * \left(1 + \sum_{1990}^{YEAR} ADJHP \right) \quad (20)$$

Note that this equation uses the sum of horsepower adjustments to date. This is necessary because the first step of the adjustment ignores the previous period result (HP_{YEAR-1}) and calculates current horsepower using the base year weight-to-horsepower ratio. The summation term incorporates all horsepower adjustments due to economic changes which occur in the intervening forecast periods. The final HP estimate is then checked to see if it meets the minimum driveability criterion which are set at WT/HP = 30 for all cars except sports and luxury for which the criterion is WT/HP = 25. These minima are derived from the experience of the early 1980's.

E: Readjust Fuel Economy and Price

Once the horsepower adjustment has been determined, the final fuel economy for the vehicle must be calculated.

Fuel Economy Adjustment Factor

The fractional change in fuel economy based on the fractional change in horsepower is first calculated (ADJFE). This is an engineering relationship expressed by the following equation:

$$ADJFE = -0.22 * ADJHP - 0.560 * ADJHP^2 \quad (21)$$

Adjusted Fuel Economy

The final vehicle fuel economy is then determined as follows:

$$FE' = FE * (1 + ADJFE) \quad (22)$$

Adjusted Vehicle Price

Vehicle price is finally estimated:

$$PRICE = PRICE + ADJHP * VALUEPERF \quad (23)$$

Note that as these are final adjustments, the results do not feed back into the horsepower adjustment equation.

The above equations result in an estimate of the market shares of the considered technologies within each class of vehicle. The next step is to calculate the market shares of each vehicle class within each CAFE group.

CALCULATE CLASS MARKET SHARES

This routine calculates vehicle class market shares within each "corporate" average fuel economy group (i.e. Domestic Cars, Import Cars, Domestic Trucks and Import Trucks.) Market shares for each class are derived by calculating an increment from the base year (1990) market share. The market share increment (or decrement) is determined by one of the following equations (depending on vehicle class):

All Vehicle Classes Except Luxury Cars:[2]

$$\ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{YEAR} - \ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{1990} = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR} - \$13{,}000}{INCOME_{1990} - \$13{,}000}\right) \quad (24)$$

where $CLASS\$SHARE_i$ is the market share of the ith market class, and the values of the coefficients A, B, and C are tabulated in Table E-1 of Appendix E.

Luxury Cars:

The calculated increment is added to the base year market share to obtain a current year value. After market shares are derived for all vehicle classes, the results are normalized so that market shares sum to 100% within each CAFE group.

$$\ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{YEAR} - \ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{1990} = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR}}{INCOME_{1990}}\right) \quad (25)$$

CALCULATE CORPORATE AVERAGE FUEL ECONOMY

This routine calculates the "corporate" average fuel economy for each of the four groups:

1) Domestic Cars
2) Import Cars
3) Domestic Trucks
4) Import Trucks

For each vehicle group the CAFE calculation proceeds as follows:

[2] Note: Market shares for Mini and Sub-Compact cars are solved jointly using equation 24. The resulting combined market share is allocated between the two classes based on the original 1990 allocation. Special treatment of these two classes was made necessary by the small sample size in the analysis data sets.

$$CAFE_{i,k,YEAR} = \frac{\sum_{i=1}^{7} CLASS\$SHARE_{i,k,YEAR}}{\sum_{i=1}^{7} \frac{CLASS\$SHARE_{i,k,YEAR}}{FE_{i,k,YEAR}}} \quad (26)$$

where:

i = Vehicle Class
k = CAFE Group

This CAFE estimate is then compared with the legislative standard for the manufacturer group and year. If the forecast CAFE is less than the standard, a second iteration of the model is performed after resetting the regulatory cost (REGCOST). If the recalculated CAFE is still below the standard, no further iteration occurs, as the manufacturer is then assumed to pay the fine.

COMBINE RESULTS OF DOMESTIC AND IMPORTED VEHICLES

In subsequent components of the transportation model, domestic and imported vehicles are not treated separately. It is therefore necessary to construct an aggregate estimate of fuel economy for each class of car and light truck. Aggregate fuel economy is determined by weighting each vehicle class by their relative share of the market. These figures are assumed to be constant across classes and time, and have been obtained from Oak Ridge estimates of the domestic and imported market shares:[3]

For Cars (except mini-compacts):

$$FE_{CLASS} = \left[\frac{.742}{FE_{CLASS,Domestic}} + \frac{.258}{FE_{CLASS,Import}} \right]^{-1} \quad (27)$$

For Light Trucks (except standard pickups, standard vans, and standard utility vehicles):

$$FE_{CLASS} = \left[\frac{.868}{FE_{CLASS,Domestic}} + \frac{.132}{FE_{CLASS,Import}} \right]^{-1} \quad (28)$$

All mini-compact cars are imported, and all standard pickups, standard vans, and standard utility vehicles are produced domestically.

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[3] Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 12*, ORNL-6710, 3/92. For Cars: Table 3.9, 1990 data. For Light Trucks: Table 3.16, 1990 data.

The fuel economies of the seven size classes described above are subsequently collapsed into six size classes considered by the remainder of the Transportation Model, and benchmarked to correspond to 1992 NHTSA estimates of fuel economy for each size class. These numbers are then passed to the Alternative Fuel Vehicle (AFV) Model, and the overall fleet stock model to produce estimates of fleet efficiencies.

3A-2. Regional Sales Model

The Regional Sales Model is a simple accounting mechanism which uses exogenous estimates of new car and light truck sales, and the results of the Fuel Economy Model to produce estimates of regional sales and characteristics of light duty vehicles, which are subsequently passed to the Light Duty Stock Model.

RATIONALE

Nationwide estimates of new car sales come from the the NEMS Macro Module. In order to comply with the NEMS requirement for regional fuel consumption estimates, the Regional Sales Model allocates new car and light truck sales among the nine Census divisions and permits regional variations in vehicle attributes. This also gives the Transportation Model the capability to analyze regional differences in alternative vehicle legislation. For example, California has implemented legislation requiring that 2% of all vehicles sold by the year 2000 be "zero emissions" vehicles (essentially electric vehicles). Massachusetts and New York have taken steps to adopt the California standards, and the Transportation Model assumes that they will be successful.

ALTERNATIVE SPECIFICATIONS

No alternative models were considered.

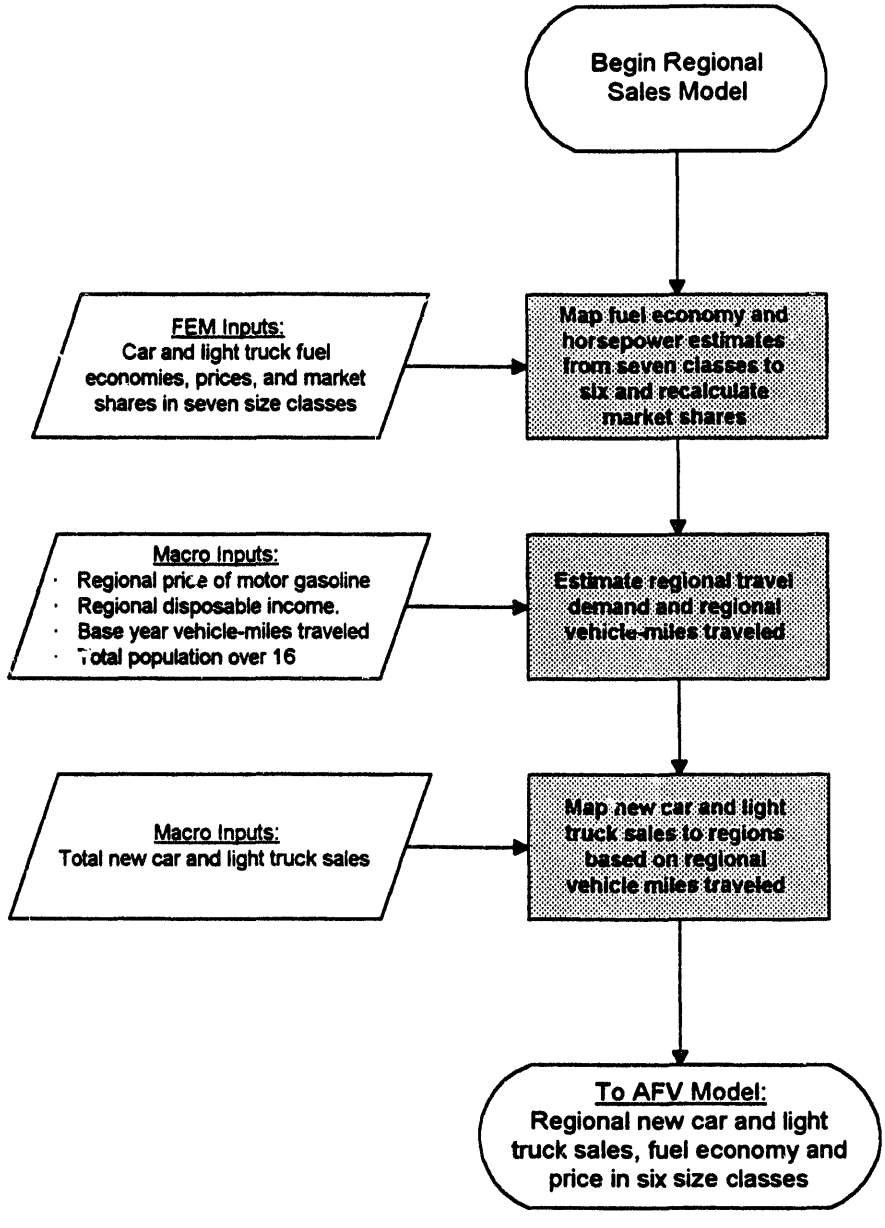
MODEL STRUCTURE

This is not a separate model in itself, but rather a series of intermediate calculations used to generate several regional variables which are used in subsequent steps in the Transportation Model. It comprises two subroutines, TSIZE and TREG; the first is used to compress the seven vehicle size classes generated by the Fuel Economy Model into six size classes used in subsequent calculations and the second generates regional shares of fuel consumption, driving

demand, and sales of vehicles by size class.

The Regional Sales Model flowchart is presented in Figure 3A-2 below.

Figure 3A-2. Regional Sales Model



Redistribute FEM Results Among Six Size Classes

The first stage in this model involves the estimation of non-fleet sales of cars and light trucks for each of the seven size classes and CAFE groups described in the Fuel Economy Model (FEM). The fraction of car and truck sales attributed to fleets is assumed to remain constant across size classes and the estimation period. Although the fuel economies of domestic and imported vehicles have already been combined, the separate market shares are recorded in the variable *MKTC*, and the calculations are performed separately for domestic and imported vehicles.

For Cars:

$$NCS7SC_{CLASS,T} = MKTC_{CLASS,T} * TMC_SQTRCARS_T * (1 - FLTCRAT_{1990}) \quad (29)$$

where:

NCS7SC = New car sales in the original seven FEM size classes
TMC_SQTRCARS = Total new car sales (supplied by the MACRO module)
MKTC = The market share for each automobile class, from FEM
FLTCRAT = Fraction of new cars purchased by fleets in 1990
T = Index referring to model run year

Similarly for Trucks:

$$NTS7SC_{CLASS,T} = MKTT_{CLASS,T} * TMC_SQDTRUCKSL_T * (1 - FLTTRAT_{1990}) \quad (30)$$

where:

NTS7SC = New light truck sales in the original seven FEM size classes
TMC_SQDTRUCKSL = Total light truck sales (supplied by the MACRO module)
MKTT = The market share for each light truck class, from FEM
FLTTRAT = Fraction of new light trucks purchased by fleets in 1990

Sales within the seven size classes are then distributed among six size classes, combining the domestic and import groups, as follows:

$$NCSTSC_{SC} = \sum_{GROUP=1}^{2} \sum_{CLASS=1}^{7} (NCS7SC_{CLASS,GROUP}) * \beta 1_{CLASS,GROUP,SC} \quad (31)$$

and:

where:

$$NLTSTSC_{SC} = \sum_{GROUP=1}^{2} \sum_{CLASS=1}^{7} (NTS7SC_{CLASS,GROUP}) * \beta 2_{CLASS,GROUP,SC} \quad (32)$$

NCSTSC = New car sales in the modified six size classes, *SC*
SC = Index for six size classes
NLTSTSC = New light truck sales
$\beta 1, \beta 2$ = Weighting coefficients associated with cars and trucks, respectively
GROUP = Index indicating domestic or imported vehicles

The market shares for cars and light trucks are then calculated by size class:

$$PASSHRR_{SC} = \frac{NCSTSC_{SC}}{\sum_{SC=1}^{6} NCSTSC_{SC}} \quad (33)$$

and:

$$LTSHRR_{SC} = \frac{NLTSTSC_{SC}}{\sum_{SC=1}^{6} NLTSTSC_{SC}} \quad (34)$$

where:

PASSHRR = Non-fleet market shares of automobiles, by size class *SC*
LTSHRR = Non-fleet market shares of light trucks, by size class *SC*

Similarly, horsepower estimates generated in FEM are compressed from seven to six size classes for cars and light trucks, combining domestic and import groups:

$$HPCAR_{SC} = \sum_{GROUP=1}^{2} \sum_{CLASS=1}^{7} (HPC_{CLASS,GROUP}) * CARSHR_{GROUP} * \beta 1_{CLASS,GROUP,SC} \quad (35)$$

and:

$$HPTRUCK_{SC} = \sum_{GROUP=1}^{2} \sum_{CLASS=1}^{7} (HPT_{CLASS,GROUP}) * TRKSHR_{GROUP} * \beta 1_{CLASS,GROUP,SC} \quad (36)$$

where:

HPCAR = Average horsepower of automobiles, by size class *SC*
HPTRUCK = Average horsepower of light trucks, by size class *SC*
HPC = Automobile horsepower by FEM size class *CLASS*

HPT = Light truck horsepower by FEM size class *CLASS*
CARSHR = Domestic vs. import market share for automobiles, from ORNL
TRKSHR = Domestic vs. import market share for light trucks, from ORNL

The average horsepower of cars and light trucks is then calculated:

$$AHPCAR_{SC} = \sum_{SC=1}^{6} HPCAR_{SC} * PASSHRR_{SC} \tag{37}$$

and:

$$AHPTRUCK_{SC} = \sum_{SC=1}^{6} HPTRUCK_{SC} * LTSHRR_{SC} \tag{38}$$

where:

AHPCAR = Average automobile horsepower
AHPTRUCK = Average light truck horsepower

Determine Regional Values of Fuel Demand and Vehicle Sales

Regional demand shares for each of eleven fuels are first initialized, ensuring that no region has a zero share in the preceding time period, then grown at the rate of personal income growth in each region, and renormalized so the shares add to 1.0:

$$SEDSHR_{FUEL,REG,T} = \frac{SEDSHR_{FUEL,REG,T-1} * \left(\frac{TMC_YD_{REG,T}}{TMC_YD_{REG,T-1}}\right)}{\sum_{REG=1}^{9} SEDSHR_{FUEL,REG,T-1} * \left(\frac{TMC_YD_{REG,T}}{TMC_YD_{REG,T-1}}\right)} \tag{39}$$

where:

SEDSHR = Regional share of the consumption of a given fuel in period *T*
TMC_YD = Estimated disposable personal income by region *REG*
REG = Index referring to Census region

These shares are passed to other modules in the Transportation Model.

The distribution of new car and light truck sales among regions is then addressed. This process takes several steps, and is based on the assumption that regional demand for new vehicles is proportional to regional travel demand. The calculation proceeds as follows:

Determine the regional cost of driving per mile:

$$COSTMIR_{REG,T} = 0.1251 * \left(\frac{TPMGTR_{REG,T}}{MPGFLT_{T-1}} \right) \tag{40}$$

where:

COSTMIR = The cost per mile of driving in region *REG*, in $/mile
TPMGTR = The regional price of motor gasoline, in $/MMBTU
MPGFLT = The previous year's stock MPG for non-fleet vehicles
.1251 = A conversion factor for gasoline, in MMBTU/gal

Calculate regional income:

$$INCOMER_{REG,T} = \left(\frac{TMC_YD_{REG,T}}{TMC_POPAFO_{REG,T}} \right) \tag{41}$$

where:

INCOMER = Regional per capita disposable income
TMC_YD = Total disposable income in region *REG*
TMC_POPAFO = Total population in region *REG*

Estimate regional driving demand:[4]

$$\begin{aligned} VMT16R_{REG,T} = {} & \rho\, VMT16R_{REG,T-1} + \beta_0 (1 - \rho) + \beta_1 \left(COSTMIR_{REG,T} - \rho\, COSTMIR_{REG,T-1} \right) \\ & + \beta_2 \left(INCOMER_{REG,T} - \rho\, INCOMER_{REG,T-1} \right) + \beta_3 \left(PRFEM_T - \rho\, PRFEM_{T-1} \right) \end{aligned} \tag{42}$$

and:

$$VMTEER_{REG,T} = VMT16R_{REG,T} * TMC_POP16_{REG,T} * DAF_T \tag{43}$$

where:

VMT16R = Vehicle-miles traveled per population over 16 years of age
PRFEM = Ratio of female to male driving rates
ρ = Lag factor for the difference equation
VMTEER = Total VMT in region *REG*
TMC_POP16 = Total regional population over the age of 16
DAF = A demographic adjustment factor, to reflect different age groups' driving patterns

[4] The development and estimation of the VMT equation is described in detail later, in the VMT Model (Section 3B-2).

Calculate regional VMT shares (RSHR):

$$RSHR_{REG,T} = \frac{VMTEER_{REG,T}}{\sum_{REG=1}^{9} VMTEER_{REG,T}} \quad (44)$$

Divide non-fleet car and light truck sales according to regional VMT shares:

$$NCS_{REG,SC,T} = NCSTSC_{SC,T} * RSHR_{REG,T} \quad (45)$$

and:

$$NLTS_{REG,SC,T} = NLTSTSC_{SC,T} * RSHR_{REG,T} \quad (46)$$

where:

NCS = New car sales, by size class and region
NLTS = New light truck sales, by size class and region

3A-3. AFV Model

The Alternative Fuel Vehicle (AFV) Model is a forecasting tool designed to support the Light Duty Vehicle (LDV) Module of the NEMS Transportation Sector Model. This model uses estimates of new car fuel efficiency obtained from the Fuel Economy Model (FEM) subcomponent of the LDV Module, and fuel price estimates generated by NEMS to generate market shares of each considered technology. The model is useful both to assess the penetration of alternative-fuel vehicles and to allow analysis of policies that might impact this penetration.

RATIONALE

The objective of the AFV model is to estimate the market penetration (market shares) of alternative-fuel vehicles during the period 1990-2030. The model provides market shares for fourteen alternative-fuel technologies in addition to the conventional gasoline and diesel technologies. The shares are projected in three stages. In the first stage the two conventional technologies are allowed to compete with a single representative alternative-fuel vehicle technology. In the second stage the overall alternative-fuel vehicle share is disaggregated among eleven competitive alternative-fuel technologies. In the third stage the electric vehicle (EV) share is distributed among four EV and hybrid technologies. Forecasts of vehicle-technology shares are developed for each of the nine U.S. Census regions.

The AFV model is an improvement over the predecessor model used in the AEO 93, which assigned market shares to four basic alternative technologies based on legislative mandates. That model left no room for consideration of technological or market-driven limitations on the penetration of AFV's, thereby limiting its usefulness in evaluating the impacts of alternative policies.

ALTERNATIVE SPECIFICATIONS

There are very few current models which attempt to estimate the market penetration of alternative fuel vehicles. The methodology used in the AFV module is based on attribute-based discrete choice techniques and logit-type choice functions described in previous reports.[5] The attribute coefficients used in the module are derived from a logit discreet-choice consumer preference model commissioned by the state of California.[6] The methodology consists of the estimation of a demand function for vehicle sales in the U.S. market and the derivation of coefficients for the vehicle and fuel attributes which portrays consumer demand. Once the demand function has been determined, projections of the changes in vehicle and fuel attributes for the considered technologies are multiplied by the corresponding attribute coefficients to produce the market share penetration for the various technologies.

An important limitation in estimating market share penetration of alternative fuel technologies is the lack of experience in consumer use of alternative technologies. Only a limited number of alternative-fuel technologies are commercially available at the present time and the vehicle options which are available are still in experimental stages of development resulting in significantly high vehicle prices. Lack of data on previous consumer purchases of alternative fuel vehicles poses a significant obstacle in estimating an equation to forecast future market share penetration. A stated preference survey performed for the California Energy Commission (CAC) which asked consumers their vehicle choice preference in reference to hypothetical scenarios is used in the AFV module. The demand function for personal vehicle choice determined from this survey is used as the source for the attribute coefficients for the AFV module.[7]

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[5] See Fulton, L., *New Technology Vehicle Penetration: A Proposal for an Analytical Framework*, Submitted to EIA, Office of Energy markets and End Use, March 17, 1991.

[6] The coefficients of the vehicle attributes derived from the Logit discrete choice model are taken from Bunch, D.S.; Bradley, M.; Golob, T.F.; Kitamura, R.; Occhiuzzo, G.P., *Demand For Clean Fuel Personal Vehicles in California: A Discrete-Choice Stated Preference Survey, CAC, Dec. 1991.*

[7] For a detailed explanation of the demand function estimation, see Bunch,D.S.; Bradley,M.; Bolob, T.F.; Kitamura,R. and Occhiuzzo, G.P., *Demand for Clean-Fuel Personal Vehicles in California: A Discrete-Choice Stated Preference Survey*, California Energy Commission, December 1991.

The demand estimation incorporates a logit discrete choice model to calculate consumer vehicle preference in relation to vehicle and fuel attributes. A survey was conducted in which respondents were asked to express their preferences for vehicles based on vehicle and fuel attributes. The stated preference survey consisted of a sample size of 692 respondents yielding 3460 observations. Based on the stated preference surveys a mathematical model was estimated to account for consumer preferences in vehicle choice.

The demand function is a logit discrete choice model that can be represented as follows:

$$\log \frac{P_i}{1 - P_i} = \beta_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_i X_i + \varepsilon_i$$

where P_i is the probability of a consumer choosing vehicle i, β_i is the constant, β_i are the coefficients of vehicle and fuel attributes and X_i are vehicle and fuel attributes.

The resulting specifications of the nested multinomial logit discrete choice model for estimating market share penetration of alternative fuel technologies from the stated preference survey are presented in Table E-2 of Appendix E. The independent variables, coefficients, t-statistics, sample size, and log-likelihood calculations are listed. The coefficient signs of the five fundamental independent variables correspond with *a priori* expectations for consumer preference and all the fundamental independent variables are significant in the model.[8]

The basic structure of the forecast component of the market share estimation for alternative fuel vehicle sales is a three-dimensional matrix format. The matrix consists of I vehicle technology types, K attributes for each technology, and T number of years for the analysis. Each cell C_{ikt} in the C matrix contains a coefficient reflecting the value of attribute k of vehicle technology i for the given year t.[9]

The calculation of the market share penetration of alternative fuel vehicle sales is expressed in the following equation:

---

[8] Several variations for the discrete-choice stated preference model for alternative fuel vehicle choice were presented in the California Energy Commission report; however, the nested multinomial logit model presented in Table 2 is the preferred model to use in the AFV module.

[9] The forecasting methodology is based on the methodology defined in the Decision Analysis Corporation of Virginia Report, *Alternative Vehicle Sales Module: Design of the Modeling Framework and Prototype Module Description*, for Energy Information Administration, Task 91-137, September 30, 1991.

$$S_{it} = P_{it} = \sum_{n=1}^{N} \frac{P_{itn}}{N}, \qquad P_{itn} = \frac{e^{V_{itn}}}{\sum_{i=1}^{I} e^{V_{itn}}}$$

where:

S_{it} = market share sales of vehicle type i in year t,

P_{it} = aggregate probability over population N of choosing type i in year t,

n = individual n from population N,

P_{itn} = probability of individual n choosing type i in year t,

V_{itn} = a function of the K elements of the vector of attributes (A) and coefficients (B), generally linear in parameters, i.e.:

$$V = \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k$$

and V is specific to vehicle i, year t, and individual n.

The above equation asserts that the share of each technology is equivalent to the aggregate probability over the population of choosing that technology, which is produced by summing the individual probability functions. The individual probabilities are a function of the ratio of the *V*'s (taken as an exponential). The market share of each vehicle type is ultimately determined by its attributes relative to the attributes of all competing vehicles.

The *C* matrix represented below is a simple illustration of the matrix format used in the market share calculation. For simplicity, a 4 by 4 matrix of four vehicle types (i = 4) and four attributes (k = 4), for individual n in year t, has been chosen.

	$C_{ik}=(\beta_{ik}X_{ik})$	k=1	k=2	k=3	k=4
$V_1=\Sigma C_{1k}$	i=1	C_{11}	C_{12}	C_{13}	C_{14}
$V_2=\Sigma C_{2k}$	i=2	C_{21}	C_{22}	C_{23}	C_{24}
$V_3=\Sigma C_{3k}$	i=3	C_{31}	C_{32}	C_{33}	C_{34}
$V_4=\Sigma C_{4k}$	i=4	C_{41}	C_{42}	C_{43}	C_{44}

The factor C_{ik} represents the product of the coefficient β_{ik} derived from the demand function and the attribute value X_{ik} for vehicle type i and attribute k.

The coefficients of the vehicle attributes in the AFV module are assumed to remain constant over time. This enables the calculation of the C matrix to be less cumbersome; however, the methodology can utilize either changing or constant coefficient values for the vehicle attributes. The C matrix is replicated for each year of the analysis and for each target group incorporated in the study. The scope of the AFV module covers a 40 year time period with 9 regional target groups, three size classes and three scenarios. A V value is produced for each of the vehicle technologies, and for each of the target regions, size and scenario during each year of the study.

A separate IKT matrix must be calculated for each individual in the population, or at least for each group of similar individuals. It is necessary to calculate P_{itn} separately for each group and average to obtain an aggregate probability and market share for each vehicle type. However, a single IKT matrix can be calculated by taking one additional step. An aggregate IKT matrix which approximates the results obtained by taking an average probability can be calculated over the individual matrices. This is dependent on the condition that the average probability function over the population equals each group probability function, not just the average of all functions. Demographic variables can be used to subdivide the population into similar groups in order to approximate this condition. These variables can be incorporated into the V_{it} expression as dummy variables, which produce separate coefficients for each population group. An example of demographic variables which subdivide the population could be family size or income level. A separate dummy variable would be used for each family size category or income level category found in the population[10].

The following equation illustrates how including demographic variables, the aggregate probability function approximates each individual probability function.

$$P_{it} \approx P_{itn} \text{ for all } n \quad \therefore \quad P_{it} \approx \frac{e^{V_{it}}}{\sum_{i=1}^{I} e^{V_{it}}}$$

Where V_{it} is a function of the K-size attribute vector containing elements taken as averages over segments of the population N, with these segments defined by dummy variables.

This allows estimation of the model using a single IKT matrix over the population.

[10] The number of dummy variables required in subdividing the population is one less than the number of groups so that if 5 family size groups were included in the module 4 dummy variables would be required.

MODEL STRUCTURE

The AFV module operates in three stages, using a bottom-up approach to determine the eventual market shares of conventional and alternative vehicles. Results from the lower stages are passed to the next higher stage in the sequence. The first step in the calculation involves the evaluation of Stage 3, in which market shares of one type of alternative vehicle, Electric Vehicles and associated hybrids, are determined. These results are then passed to Stage 2, in which market shares for all alternative vehicles are estimated. The average characteristics of alternative vehicles are subsequently passed to Stage 1, where the final mix of alternative and conventional vehicles is calculated.

An additional constraint is included at each stage of the market share calculation which incorporates commercial availability of the alternative-fuel technology. The aggregate probability function assumes that all technologies are fully developed and available to the consumer at the present time. This assumption does not hold true for most of the alternative-fuel technologies, which at the present time still remain in development stages. Therefore, an upper limit constraint is placed on the market share penetration of alternative vehicle sales corresponding to the expected development and commercial availability of alternative fuel vehicles. This constraint applies to the early years and is gradually reduced through the forecasting period, via a logistic curve for each technology. The equations associated with each stage of the model are presented below, in order of execution.

The Alternative Fuel Vehicle Model flowchart is presented in Figure 3A-3 below. More detailed sketches of AFV calculations are presented at the end of Section 3A.

STAGE 3

Stage 3 of the AFV module determines the market share of each of the four EV technologies considered in the model. These market shares are used to characterize a prototypic EV when all alternative vehicles are considered in Stage 2. The steps involved in Stage 3 are described below.

1) Calculate the weighted average fuel price for each EV technology, by region.

$$AFCOST_{EVTECH,REG} = \frac{\sum_{FUEL} (RFP_{FUEL,REG} \cdot FAVAIL_{FUEL,REG})}{\sum_{FUEL} FAVAIL_{FUEL,REG}} \quad (47)$$

where:

AFCOST = Electric vehicle fuel price, in 1990$ / MMBTU

RFP = Price of each fuel used by the corresponding EV technology
FAVAIL = Relative availability of the corresponding fuel
EVTECH = Index referring the electric vehicle technology
FUEL = Index referring to fuel used by technology *EVTECH*

2) Calculate EV operating costs, by region.

$$COPCOST_{EVTECH,REG} = \frac{AFCOST_{EVTECH,REG}}{BASEFF \cdot VEFFBTU_{EVTECH}} \tag{48}$$

where:

COPCOST = Fuel operating costs for each technology, in 1990 cents per mile
BASEFF = Baseline efficiency of gasoline internal combustion engines (ICEs), in MPG
VEFFBTU = Efficiency of a given EV technology relative to the gasoline ICE

3) Determine fuel availability relative to gasoline, $FAVAIL_{EVTECH,REG}$, using the highest value associated with any of the fuels used in electric hybrids.

$$FAVAIL_{EVTECH,REG} = MAX\,(FAVAIL_{FUEL,REG}) \tag{49}$$

4) Calculate the logit function inputs from the attributes and coefficients, by region.

$$\begin{aligned} EVECT_{EVTECH,REG} = EXP\,[\,&BETACONST_{EVTECH} + \beta_1 VPRICE_{EVTECH} + \beta_2 COPCOST_{EVTECH,REG} \\ &+ \beta_3 VRANGE_{EVTECH} + \beta_4 VRANGE^2_{EVTECH} + \beta_5 VEMISS_{EVTECH} \\ &+ \beta_6 VEMISS^2_{EVTECH} + \beta_7 FAVAIL_{EVTECH,REG} + \beta_8 FAVAIL^2_{EVTECH,REG}\,] \end{aligned} \tag{50}$$

where:

BETACONST = Constant associated with each EV technology
VPRICE = Price of each EV technology in 1990$
VRANGE = Vehicle range of the considered technology
VEMISS = Emissions levels relative to gasoline ICE's

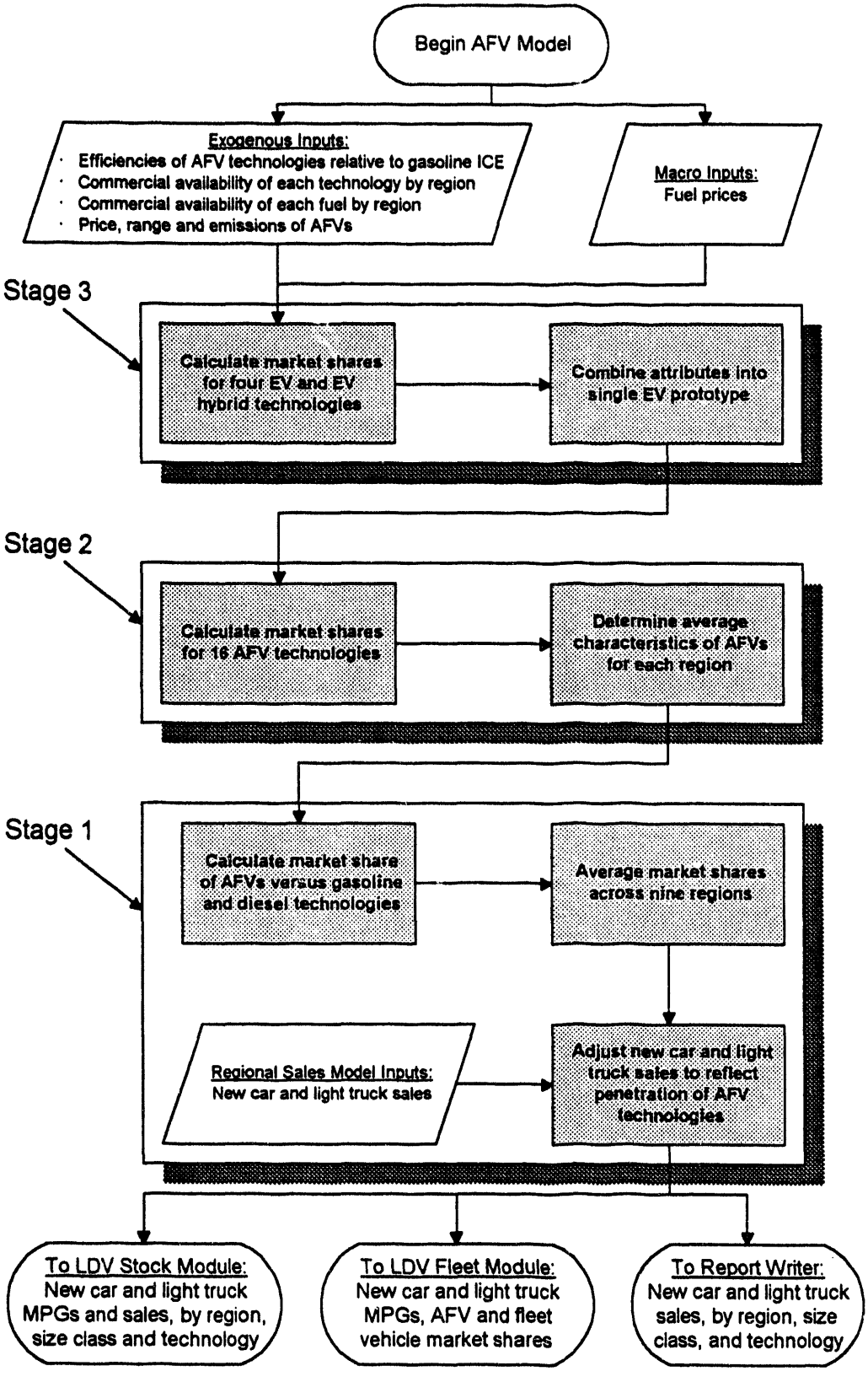
5) Calculate EV market shares, by region.

$$APSHR33_{EVTECH,REG} = \frac{EVECT_{EVTECH,REG} \cdot COMAVAIL_{EVTECH}}{\sum_{EVTECH=1}^{4} (EVECT_{EVTECH,REG} \cdot COMAVAIL_{EVTECH})} \tag{51}$$

where:

APSHR33 = Relative market shares of each EV technology
COMAVAIL = Commercial availability of each technology

Figure 3A-3. Alternative Vehicle Model



6) Calculate average market shares across Census regions:

$$APSHR33_{EVTECH} = \frac{1}{9} \sum_{REG=1}^{9} APSHR33_{EVTECH,REG} \tag{52}$$

7) Determine the characteristics of a prototypical EV technology by weighting the individual technologies' characteristics by their respective market shares.

$$\Psi_{EV} = \sum_{EVTECH=1}^{4} \Psi_{EVTECH} \cdot APSHR33_{EVTECH} \tag{53}$$

where Ψ_{EV} denotes the average attributes of the EV technologies: vehicle price, efficiency, relative emissions, range, commercial availability, and alternative-specific constant. A similar procedure is used to characterize regional attributes such as fuel price and availability, and operating costs. These attributes are used as inputs in the Stage 2 subroutine.

STAGE 2

Stage 2 determines the relative market shares among the set of alternative vehicles. The result of this step is a prototypic AFV whose characteristics are determined by the market share-weighted attributes of all 11 alternative vehicle types. The sequence of calculations replicates those conducted in Stage 3, and is presented below.

8) Calculate the weighted average fuel price for each AFV technology, by region.

$$AFCOST_{AFVTECH,REG} = \frac{\sum_{FUEL} (RFP_{FUEL,REG} \cdot FAVAIL_{FUEL,REG})}{\sum_{FUEL} FAVAIL_{FUEL,REG}} \tag{54}$$

where:

AFCOST = Alternative vehicle fuel price, in 1990$ / MMBTU
AFVTECH = Index referring to AFV technology

9) Calculate AFV operating costs, by region.

$$COPCOST_{AFVTECH,REG} = \frac{AFCOST_{AFVTECH,REG}}{BASEFF \cdot VEFFBTU_{AFVTECH}} \tag{55}$$

where:

COPCOST = Fuel operating costs for each technology, in 1990$ per mile

VEFFBTU = Efficiency of a given AFV technology relative to the gasoline internal combustion engine

10) Determine fuel availability relative to gasoline, $FAVAIL_{AFVTECH,REG}$, which is set to the highest value associated with the group of fuels used in multi-fuel vehicles.

$$FAVAIL_{AFVTECH,REG} = MAX\ (FAVAIL_{FUEL,REG}) \tag{56}$$

11) Calculate the logit function inputs from the attributes and coefficients, by region.

$$\begin{aligned} AFVECT_{AFVTECH,REG} = EXP\ [\ & BETACONST_{AFVTECH} + \beta_1 VPRICE_{AFVTECH} + \beta_2 COPCOST_{AFVTECH,REG} \\ & + \beta_3 VRANGE_{AFVTECH} + \beta_4 VRANGE^2_{AFVTECH} + \beta_5 VEMISS_{AFVTECH} \\ & + \beta_6 VEMISS^2_{AFVTECH} + \beta_7 FAVAIL_{AFVTECH,REG} + \beta_8 FAVAIL^2_{AFVTECH,REG}\ ] \end{aligned} \tag{57}$$

where:

BETACONST = Constant associated with each AFV technology
VPRICE = Price of each AFV technology in 1990$
VRANGE = Vehicle range of the considered technology
VEMISS = Emissions levels relative to gasoline ICE's

12) Calculate AFV market shares, by region.

$$APSHR22_{AFVTECH,REG} = \frac{AFVECT_{AFVTECH,REG} \cdot COMAVAIL_{AFVTECH}}{\sum_{AFVTECH=1}^{11} (AFVECT_{AFVTECH,REG} \cdot COMAVAIL_{AFVTECH})} \tag{58}$$

where:

APSHR22 = Relative market shares of each AFV technology
COMAVAIL = Commercial availability of each technology

13) Determine average characteristics of AFV's for each region, for use in Stage 1.

$$\Psi_{AFV,REG} = \sum_{AFVTECH=1}^{11} \Psi_{AFVTECH,REG} \cdot AFVMSH_{AFVTECH,REG} \tag{59}$$

STAGE 1

Stage 1 determines the final mix of conventional and alternative technologies, using the share-weighted average characteristics of AFV's determined in Stage 2. Three technologies are considered in this stage: gasoline, diesel, and alternatives.

14) Calculate the logit function inputs from the attributes and coefficients, by region.

$$\begin{aligned} VECT_{TECH,REG} = EXP\,[&BETACONST_{TECH} + \beta_1 VPRICE_{TECH} + \beta_2 COPCOST_{TECH,REG} \\ &+ \beta_3 VRANGE_{TECH} + \beta_4 VRANGE^2_{TECH} + \beta_5 VEMISS_{TECH} \\ &+ \beta_6 VEMISS^2_{TECH} + \beta_7 FAVAIL_{TECH,REG} + \beta_8 FAVAIL^2_{TECH,REG}\,] \end{aligned} \tag{60}$$

where:

BETACONST = Constant associated with each technology
VPRICE = Price of each technology in 1990$
VRANGE = Vehicle range of the considered technology
VEMISS = Emissions levels relative to gasoline ICE's
TECH = Index referring to the three major vehicle technologies: gasoline, diesel & alternative

15) Calculate market shares, by region.

$$APSHR11_{TECH,REG} = \frac{VECT_{TECH,REG} \cdot COMAVAIL_{TECH}}{\sum_{TECH} (VECT_{TECH,REG} \cdot COMAVAIL_{TECH})} \tag{61}$$

where:

APSHR11 = Relative market shares of each technology
COMAVAIL = Commercial availability of each technology

16) Average market shares across nine regions.

$$APSHR11_{TECH} = \frac{1}{9} \sum_{REG=1}^{9} APSHR11_{TECH,REG} \tag{62}$$

The final step is to combine the market shares of the preceding three stages to produce absolute market shares of each of the sixteen technologies addressed in this model. The absolute regional market shares of gasoline and diesel vehicles remain unchanged from those calculated in Stage 1, the AFV market shares from Stage 2 are adjusted by the total alternative market share from Stage 1, and the EV market shares from Stage 3 are modified by the adjusted electric vehicle market share. These values are placed in $APSHR44_{IT,REG}$, where *IT* represents the expanded sixteen technologies.

For gasoline and diesel vehicles (TECH = 1,2):

$$APSHR44_{IT,REG} = APSHR33_{TECH,REG} \tag{63}$$

For non-electric AFV's (TECH = 3, AFVTECH ≠ 9):

$$APSHR44_{IT,REG} = APSHR33_{AFV} * APSHR22_{AFVTECH} \quad (64)$$

For electric AFV's (TECH = 3, AFVTECH = 9):

$$APSHR44_{IT,REG} = APSHR33_{AFV} * APSHR22_{EV} * APSHR11_{EVTECH} \quad (65)$$

Regional sales of new cars and light trucks may then be calculated, disaggregated by six size classes and by technology:

$$NCSTECH_{IT,REG,SC} = APSHR_{IT,REG,SC} * NCS_{REG,SC} \quad (66)$$

and:

$$NLTECH_{IT,REG,SC} = APSHR_{IT,REG,SC} * NLTS_{REG,SC} \quad (67)$$

where:

NCSTECH = Regional new car sales, by size class and technology
NLTECH = Regional new light truck sales, by size class and technology
APSHR = Absolute regional market shares of each vehicle technology
NCS = Regional new car sales, from the Regional Sales Model
NLTS = Regional new light truck sales, from the Regional Sales Model

These values are subsequently passed to the LDV Stock Module, in which the average attributes of the fleet of private light-duty vehicles are determined.

Figure 3A-4. Fuel Economy Model 1: Economic Market Share Calculation

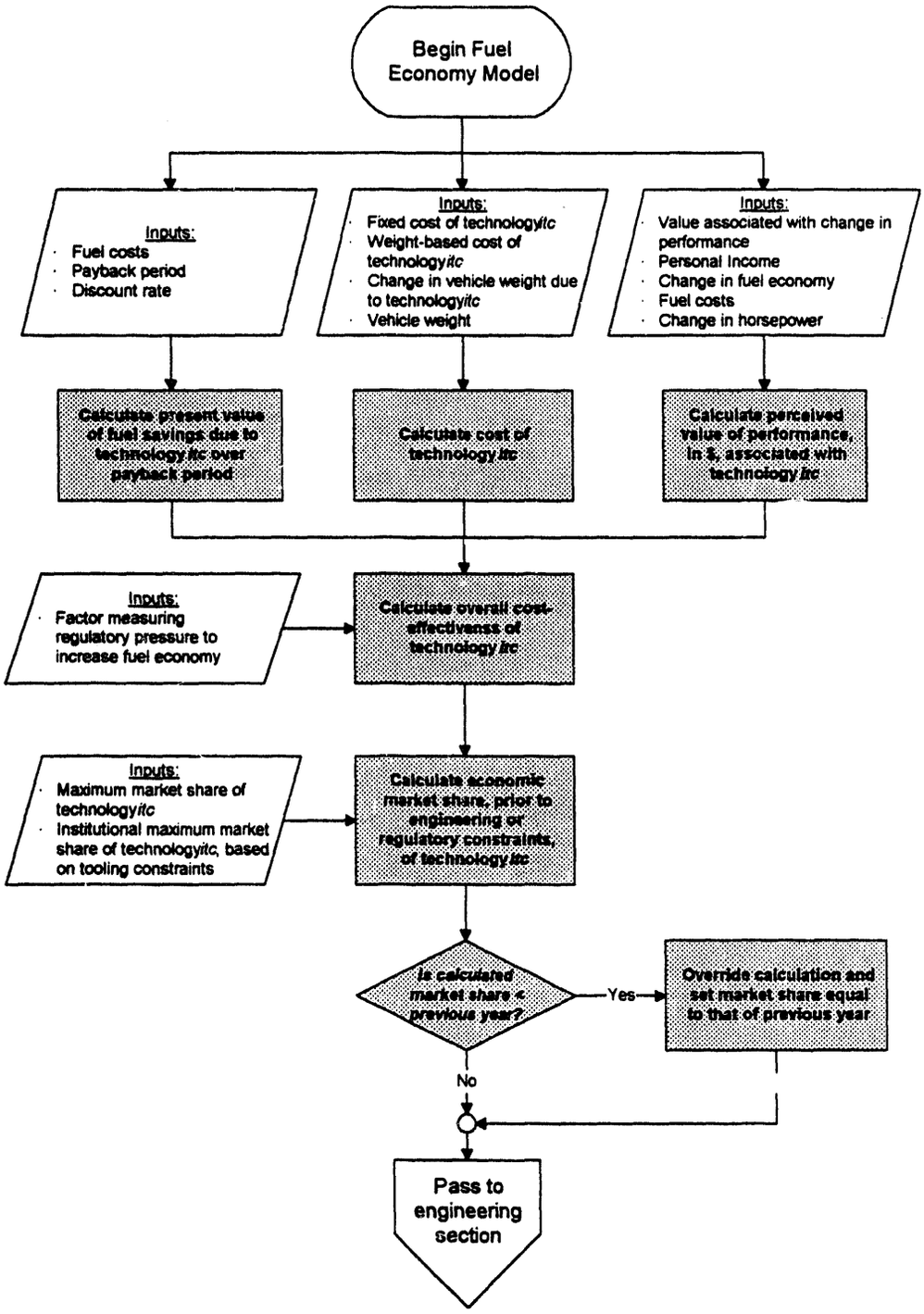


Figure 3A-5. Fuel Economy Model 2: Engineering Notes

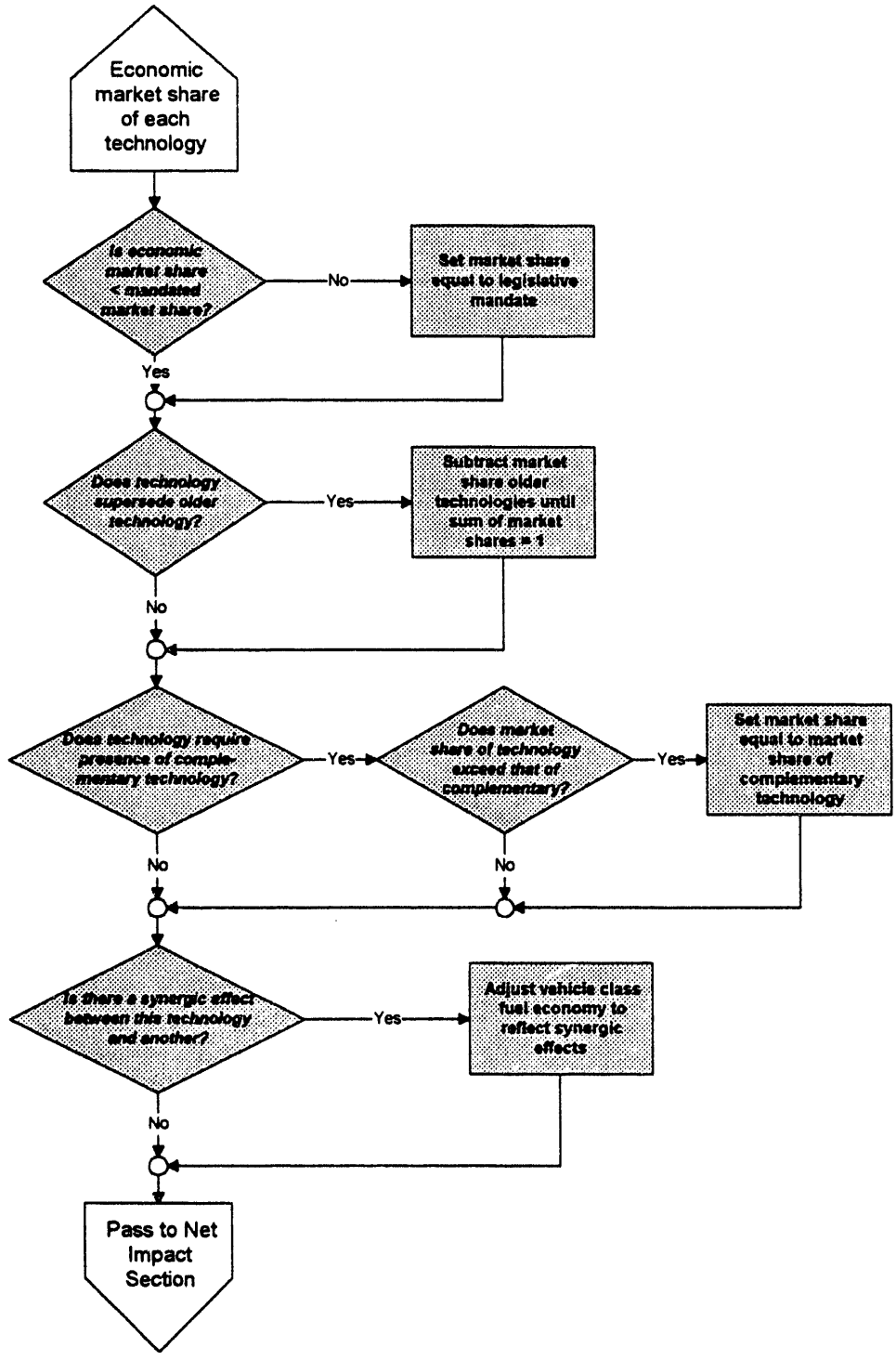


Figure 3A-6. Fuel Economy Model 3: Weight and Horsepower Calculations

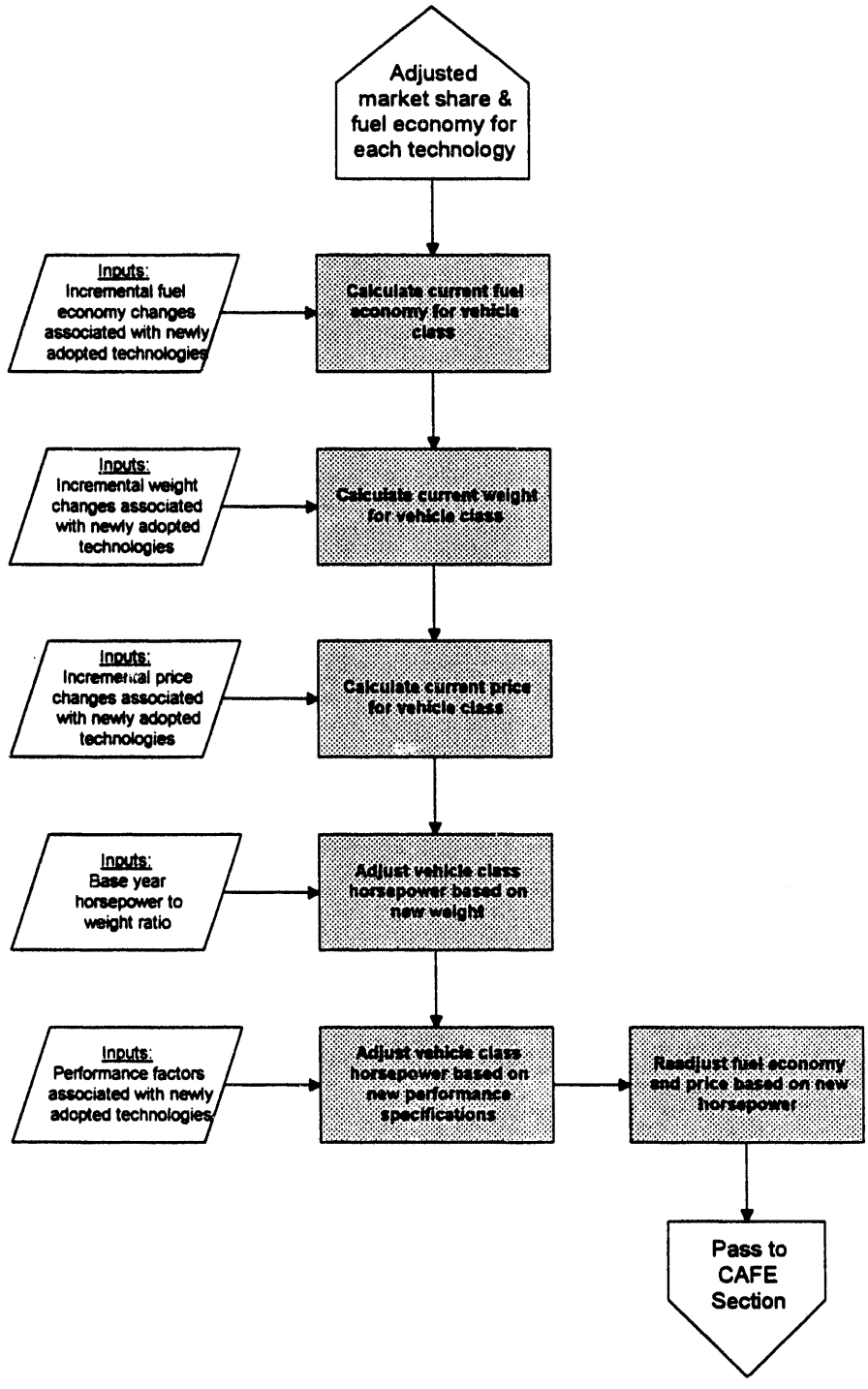


Figure 3A-7. Fuel Economy Model 4: CAFE Calculations

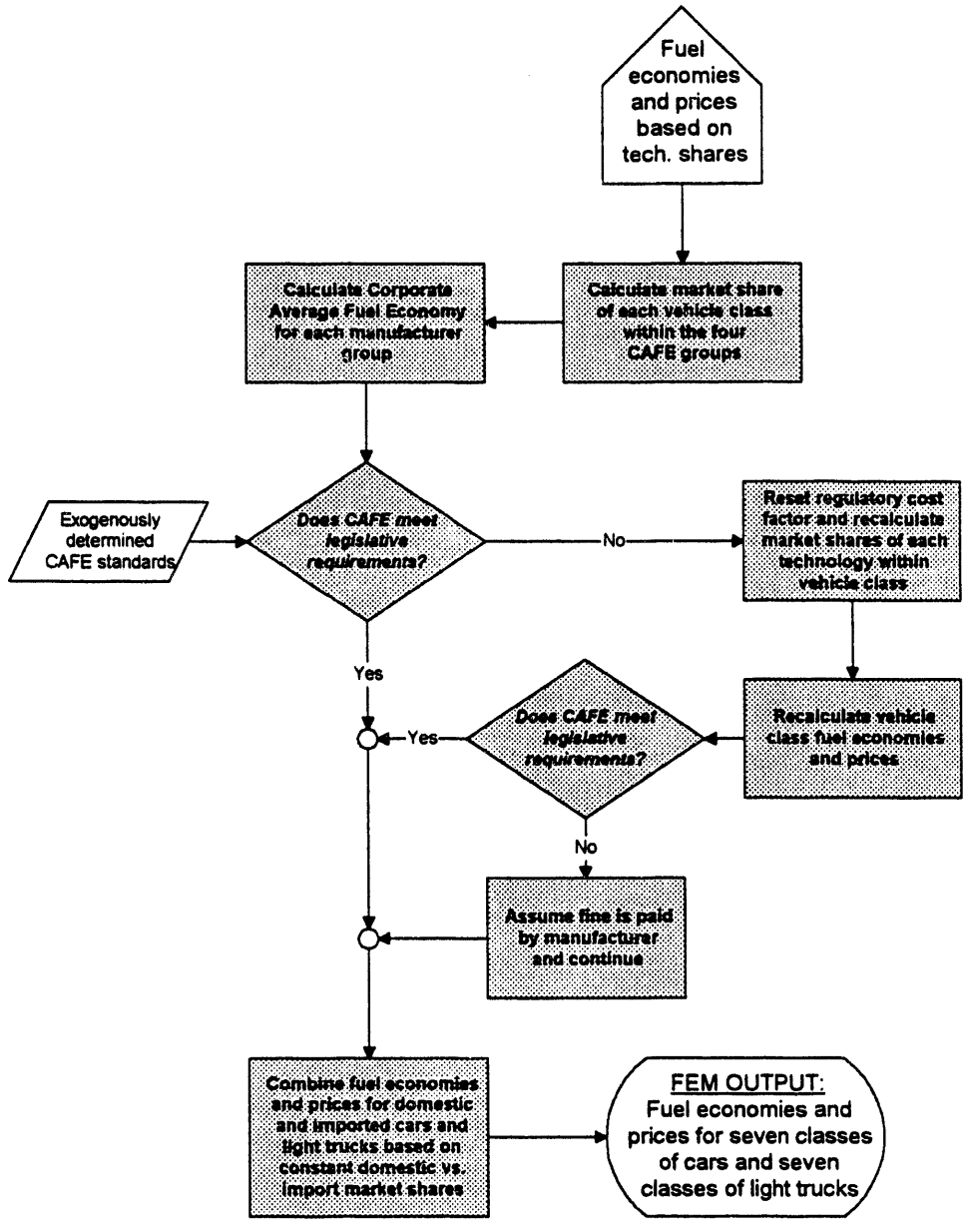


Figure 3A-8: Alternative Fuel Vehicle Model Stage 3

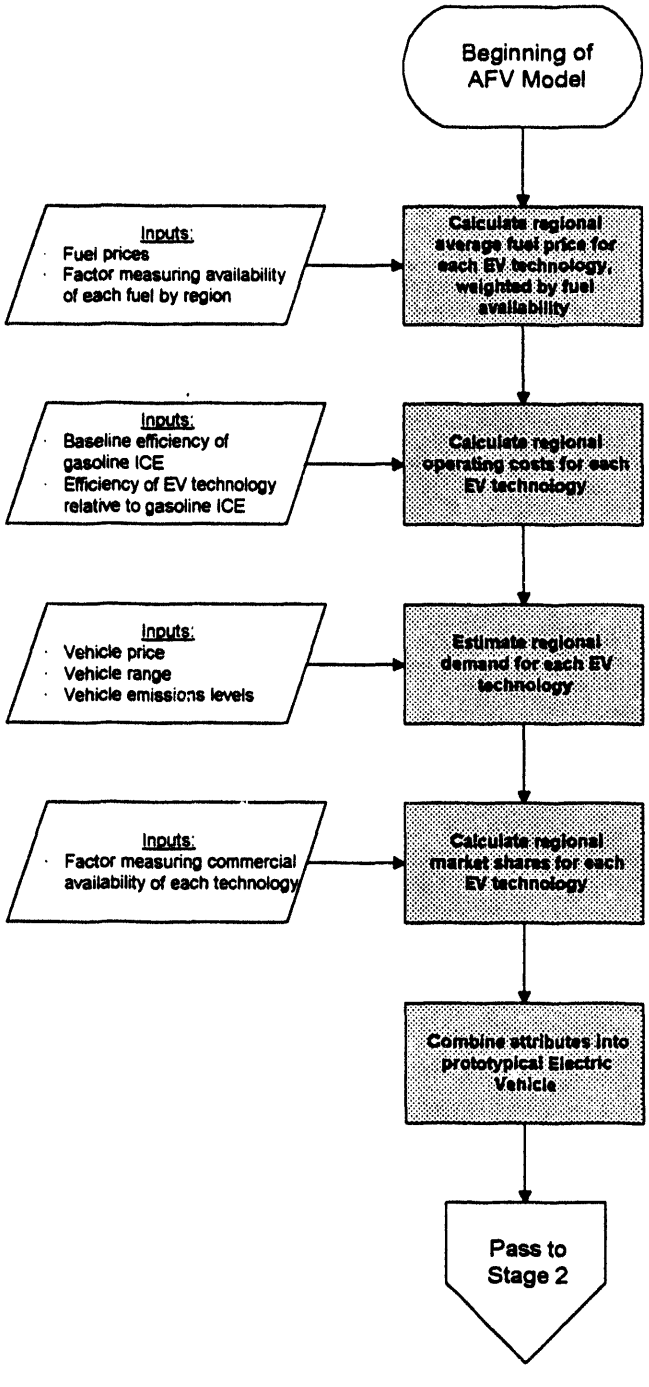


Figure 3A-9: Alternative Fuel Vehicle Model Stage 2

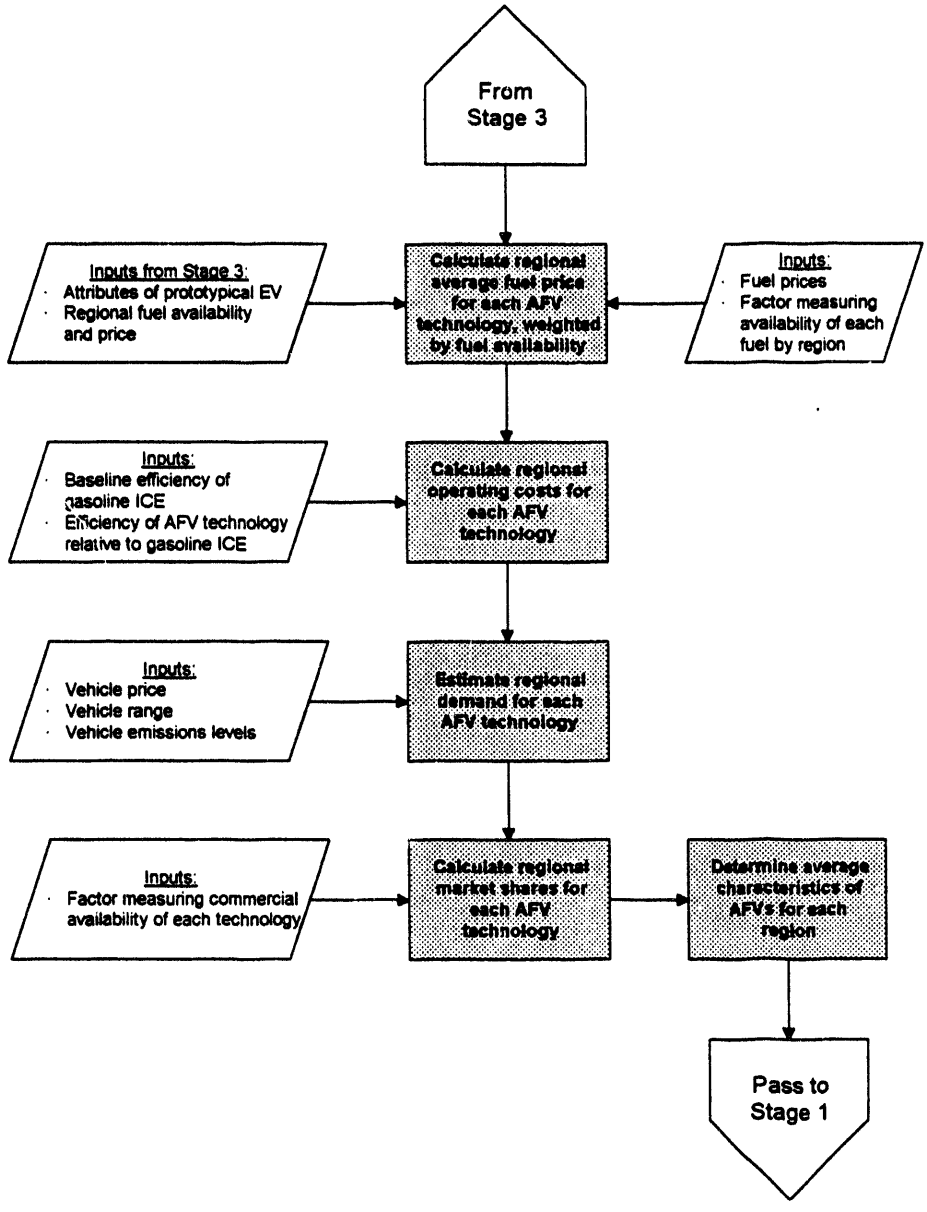
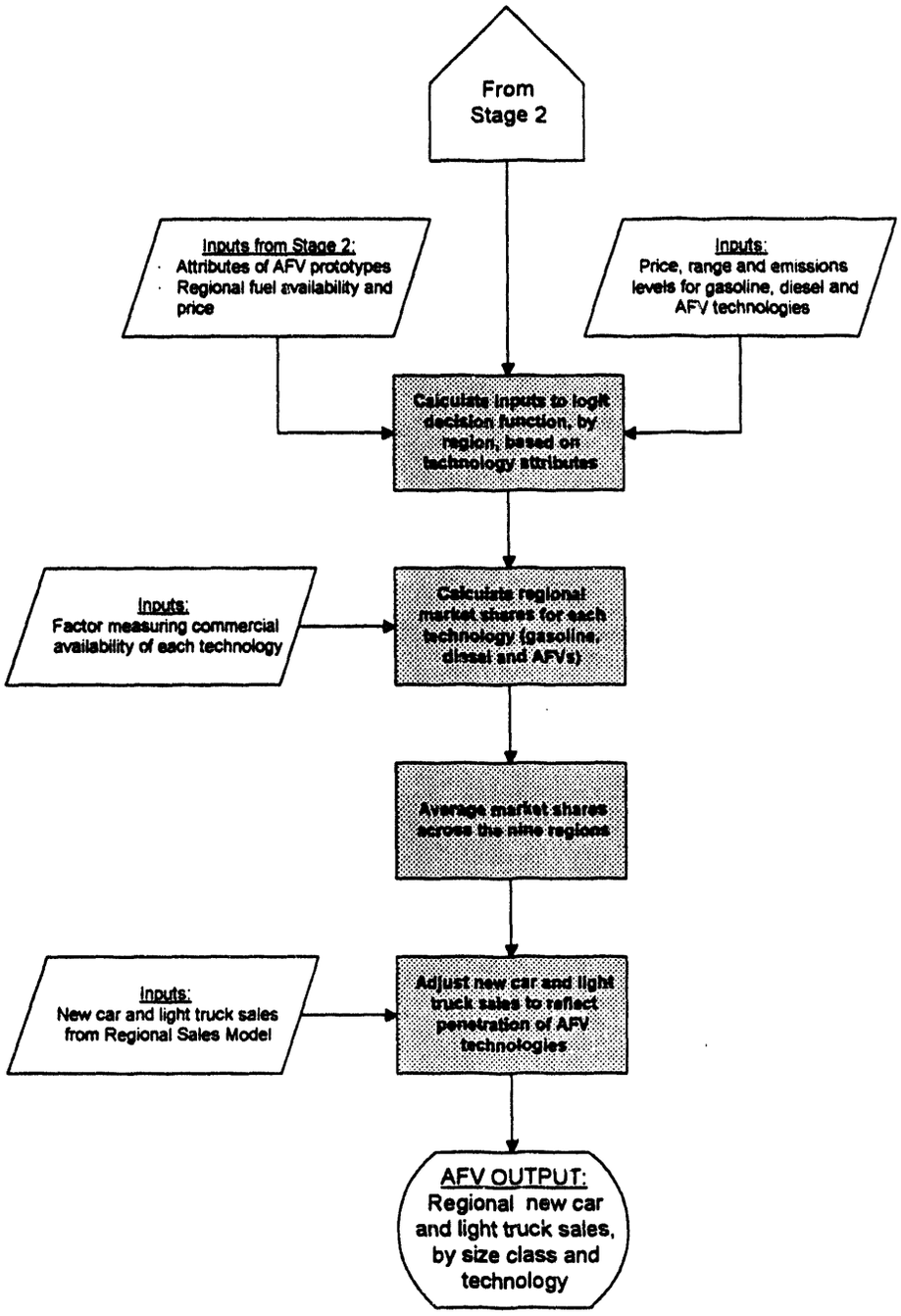


Figure 3A-10: Alternative Fuel Vehicle Model Stage 1



3B. LDV Stock Module

The Light Duty Vehicle Stock Module takes sales and efficiency estimates for new cars and light trucks from the LDV Module, and returns the number and characteristics of the total surviving fleet of light-duty vehicles, along with regional estimates of LDV fuel consumption.

The Light Duty Vehicle Stock Module flowchart is presented in Figure 3B-1 below. More detailed sketches of LDV Stock calculations are presented at the end of Section 3B.

3B-1. LDV Stock Accounting Model

RATIONALE

The existing stock model is perhaps the most important transportation sector model, since by far the largest portion of transportation energy consumption is accounted for by light duty vehicles that are at least a year old. The LDV Stock Accounting Module takes the results of the LDV Module, i.e., the number and characteristics of newly purchased cars and light trucks, and integrates those into the existing stock of vehicles, taking into account vehicle retirements and vehicles which are transferred from fleets to private ownership. The result is a snapshot of the "average" car for each region.

These characterstics are passed to the VMT Model, which determines the average number of miles driven by each vehicle in the current year. The product then becomes the regional fuel consumption estimate.

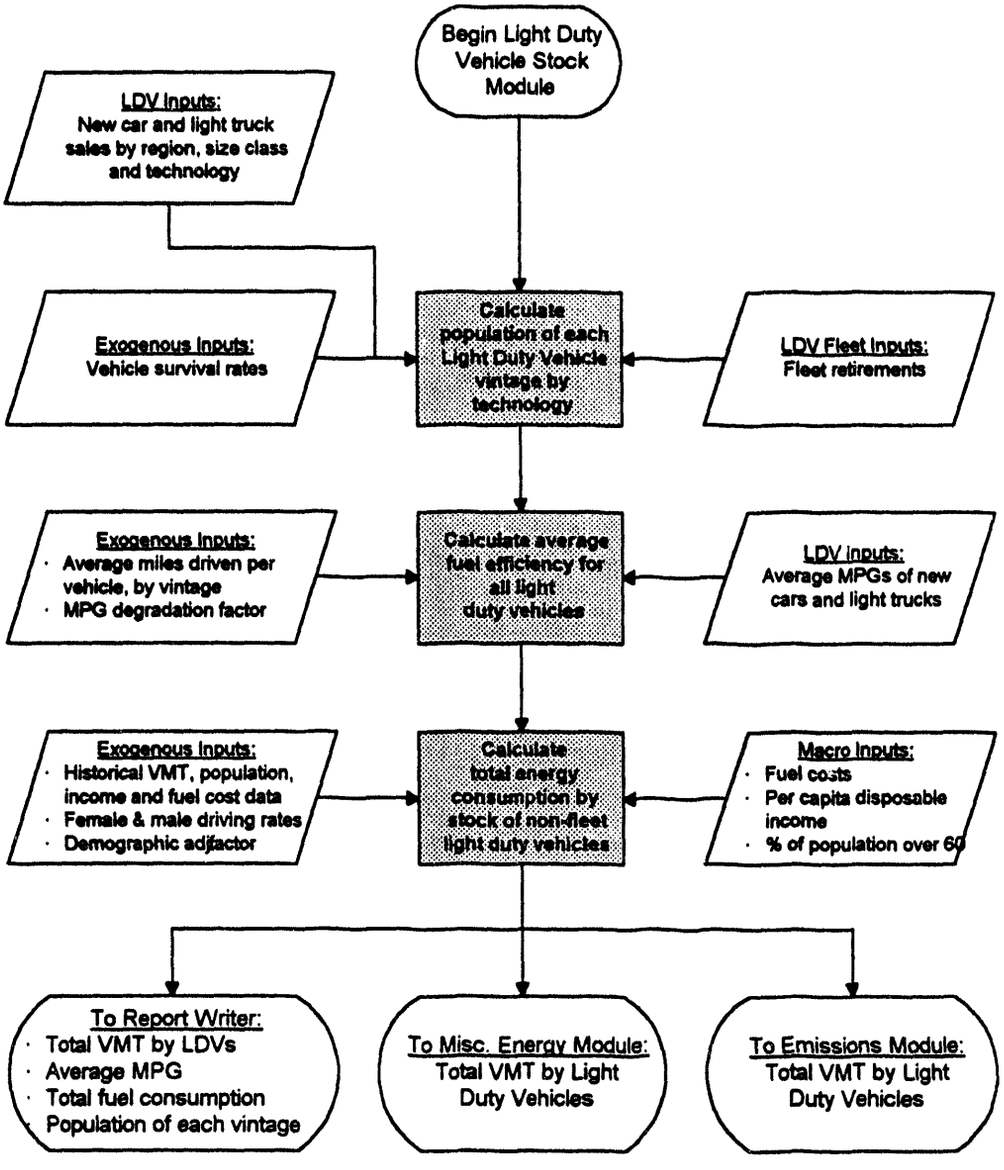
ALTERNATIVE SPECIFICATIONS

No alternative models were considered.

MODEL STRUCTURE

The flowchart for the LDV Stock Module is presented below in Figure 3B-1. More detailed flowcharts are presented at the end of this section.

Figure 3B-1. Light Duty Vehicle Stock Module



The first step is to calculate total vehicle sales by technology for the current time period:

$$TECHNCS_{IT} = \sum_{SC=1}^{8} \sum_{REG=1}^{9} NCSTECH_{IT,REG,SC}$$

and: (68)

$$TECHNLT_{IT} = \sum_{SC=1}^{8} \sum_{REG=1}^{9} NLTECH_{IT,REG,SC}$$

where:

TECHNCS = Total new car sales, by technology
TECHNLT = Total new light truck sales, by technology
NCSTECH = New car sales, by region, size class, and technology, from the AFV Model
NLTECH = New light truck sales, by region, size class, and technology, from the AFV Model

These variables are assigned to the first vintages of the automobile and light truck stock arrays, and the population of subsequent vintages are calculated:

$$PASSTK_{IT,VINT,T} = PASSTK_{IT,VINT-1,T-1} * SSURVP_{VINT-1}$$

and: (69)

$$LTSTK_{IT,VINT,T} = LTSTK_{IT,VINT-1,T} * SSURVLT_{VINT-1}$$

where:

PASSTK = Surviving automobile stock, by technology and vintage
LTSTK = Surviving light truck stock, by technology and vintage
SSURVP = Fraction of a given vintage's automobiles which survive
SSURVLT = Fraction of a given vintage's light trucks which survive
VINT = Index referring to vintage, or age of vehicle

The model encompasses ten vintages, with the tenth being an aggregation of all vehicles 10 years old or older. SSURVP and SSURVLT thus each contain ten values measuring the percentage of vehicles of each vintage which survive into the next year. These values are taken from the ORNL Transportation Energy Data Book, which lists scrappage and survival rates for 25 vintages. Survival rates for vintages 10 through 25 were simply averaged to collapse ORNL's 25 vintages into the 10 used by the Transportation Model.

The stock of selected vintages and technologies calculated above is then augmented by a number of fleet vehicles which are assumed to roll over into the non-fleet population after a number of years of fleet service:

$$PASSTK_{IT,TVINT} = PASSTK_{IT,TVINT} + OLDFSTK_{CAR,TYPE,ITECH,TVINT}$$

and: (70)

$$LTSTK_{IT,TVINT} = LTSTK_{IT,TVINT} + OLDFSTK_{TRUCK,TYPE,ITECH,TVINT}$$

where:

OLTFSTK = Number of fleet vehicles rolled over into corresponding private categories
TVINT = Transition vintage: vintage at which vehicles of a given type are transferred
TYPE = Type of fleet vehicle: Business, Government, or Utility
ITECH = Index for the six fleet vehicle technologies: mapped to corresponding *IT* index

Total stocks of cars and trucks are then determined by summing over vintages and technologies:

$$STKCAR_T = \sum_{VINT=1}^{10} \sum_{IT=1}^{16} PASSTK_{IT,VINT,T}$$

and: (71)

$$STKTR_T = \sum_{VINT=1}^{10} \sum_{IT=1}^{16} LTSTK_{IT,VINT,T}$$

where:

STKCAR = Total stock of non-fleet automobiles in year *T*
STKTR = Total stock of non-fleet light trucks in year *T*

The share of each technology in the total LDV stock is finally calculated:

$$VSPLDV_{IT,T} = \frac{\sum_{VINT=1}^{10} \left(PASSTK_{IT,VINT,T} + LTSTK_{IT,VINT,T}\right)}{STKCAR_T + STKTR_T} \quad (72)$$

where:

VSPLDV = The light duty vehicle shares of each of the sixteen vehicle technologies

The above variables are then passed to the subroutine TMPGSTK to determine average fuel efficiencies of the current year's stock of non-fleet vehicles.

Calculate Stock Efficiencies for Cars and Light Trucks

Overall fuel efficiency is calculated as the weighted average of the efficiencies of new vehicles and the efficiencies of the surviving vintages. The Alternative Fuel Vehicle Model generates

efficiency estimates for fifteen non-gasoline technologies in three size classes, with no distinction made between cars and light trucks. Because conventional truck efficiencies are generally lower than automobiles in the corresponding size class, a series of ratios is first calculated in order to adjust downwards the AFV efficiency estimates of light trucks:

$$\mathbf{RATIO}_{ASC,T} = \frac{\mathbf{AMPGT}_{ASC,T}}{\mathbf{AMPGC}_{ASC,T}} \tag{73}$$

where:

AMPGT = The average MPG of trucks, in three size classes
AMPGC = The average MPG of cars, in three size classes
ASC = The three AFV size classes, onto which the six primary size classes are mapped

The average efficiencies of the fifteen non-gasoline technologies are calculated as follows:

$$\mathbf{MPGC}_{IT,T} = \left[\sum_{ASC=1}^{3} \frac{\mathbf{MSHC}_{IT,ASC,T}}{\mathbf{NAMPG}_{IT,ASC,T}} \right]^{-1}$$

and: (74)

$$\mathbf{MPGT}_{IT,T} = \left[\sum_{ASC=1}^{3} \frac{\mathbf{MSHLT}_{IT,ASC,T}}{\mathbf{NAMPG}_{IT,ASC,T} * \mathbf{RATIO}_{ASC,T}} \right]^{-1}$$

where:

MPGC = New car fuel efficiency, by engine technology
MPGT = New light truck fuel efficiency, by engine technology
MSHC = The share of cars of size class *ASC* and technology *IT* in total car sales, from the AFV model
MSHLT = The share of light trucks of size class *ASC* and technology *IT* in total light truck sales
NAMPG = New AFV fuel efficiency, from the AFV model

For conventional technologies, when *IT* refers to gasoline ICE's, the calculation is similar, but over six size classes:

$$\mathbf{MPGC}_{IT,T} = \left[\sum_{SC=1}^{6} \frac{\mathbf{MSHC}_{IT,SC,T}}{\mathbf{NCMPG}_{SC,T}} \right]^{-1}$$

and: (75)

$$\mathbf{MPGT}_{IT,T} = \left[\sum_{SC=1}^{6} \frac{\mathbf{MSHLT}_{IT,SC,T}}{\mathbf{NLTMPG}_{SC,T}} \right]^{-1}$$

where:

NCMPG = New car MPG, from the FEM model

NLTMPG = New light truck MPG, from the FEM model

The average fuel efficiency across all technologies is then calculated for cars and trucks, and the result sent to the report writer:

$$ANCMPG_T = \left[\sum_{IT=1}^{16} \frac{APSHRNC_{IT,T}}{MPGC_{IT,T}} \right]$$

and: (76)

$$ANTMPG_T = \left[\sum_{IT=1}^{16} \frac{APSHRNT_{IT,T}}{MPGT_{IT,T}} \right]$$

where:

ANCMPG = Average new car MPG
ANTMPG = Average new light truck MPG
APSHRNC = Absolute market share of new cars, by technology, from the AFV model
APSHRNT = Absolute market share of new light trucks, by technology, from the AFV model

The overall fuel efficiency of cars and light trucks is then calculated across the ten vintages addressed in the model.[11] Since older vehicles are driven less than newer vehicles, it is necessary to weight the fuel efficiencies of each vintage according to the average number of miles driven. This is done by summing the total number of miles driven across all vintages and technologies:[12]

$$TOTMICT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} PASSTK_{IT,IV,T} * PVMT_{IV}$$

and: (77)

$$TOTMITT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} LTSTK_{IT,IV,T} * LVMT_{IV}$$

where:

TOTMICT = Total miles driven by cars
TOTMITT = Total miles driven by light trucks
PVMT = Average miles driven by each vintage of automobile, from RTECS
LVMT = Average miles driven by each vintage of light truck, from RTECS

The next step is to calculate the total energy consumed across all vintages and technologies of cars and light trucks. Since the on-road fuel efficiency of cars and trucks degrades over time,

[11] Initial (1990) values for on-road car and light truck fleet MPG are obtained from the 1991 RTECS.

[12] Vehicle-miles calculated in this step are used to establish relative driving rates for the various technologies. Actual travel demand is generated by the model in a subsequent step.

vintage fuel efficiencies must be adjusted using degradation factors (which are assumed to remain constant over time):

$$CMPGT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} \frac{PASSTK_{IT,IV,T} * PVMT_{IV}}{CMPGSTK_{IT,IV,T} * CDF_T}$$

and: (78)

$$TMPGT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} \frac{LTSTK_{IT,IV,T} * LVMT_{IV}}{TTMPGSTK_{IT,IV,T} * LTDF_T}$$

where:

CMPGT = Automobile stock MPG
TMPGT = Light truck stock MPG
CMPGSTK = Automobile stock MPG, by vintage and technology
TTMPGSTK = Light truck stock MPG, by vintage and technology
CDF = Automobile fuel efficiency degradation factor
LTDF = Light truck fuel efficiency degradation factor

Stock fuel efficiency is then simply the ratio of total travel to total consumption for cars and light trucks:

$$SCMPG_T = \frac{TOTMICT_T}{CMPGT_T}$$

and: (79)

$$STMPG_T = \frac{TOTMITT_T}{TMPGT_T}$$

Combining the results for cars and trucks provides the average fuel efficiency for all light duty vehicles:

$$MPGFLT = \frac{TOTMICT_T + TOTMITT_T}{CMPGT_T + TMPGT_T} \quad (80)$$

where:

SCMPG = Stock MPG for automobiles
STMPG = Stock MPG for light trucks
MPGFLT = Stock MPG for all light duty vehicles

These fuel efficiency figures are combined with the results of the subsequent VMT module to determine the actual fuel consumption by light duty vehicles.

3B-2. VMT Model

The travel demand component of the NEMS Transportation Model is a sub-component of the Light Duty Vehicle Stock Module which uses NEMS estimates of fuel price and personal income, along with population projections to generate a forecast of the demand for personal travel, expressed in vehicle-miles traveled (VMT). This is subsequently combined with forecasts of automobile fleet efficiency to estimate fuel consumption.

RATIONALE

Because personal automobile travel accounts for such a significant fraction of total energy consumption, it is important to ensure that the model which forecasts this travel demand be as accurate as possible. This accuracy is measured not so much by the predictive "success" of the model, but by the sensitivity of the model to the economic and policy levers which are of concern to the users, and by the ability of the model to respond to both short-term economic factors, and long-term demographic and structural trends. The model described in this section is an attempt to provide a more intuitive and inclusive approach to demographic influences in the estimation of travel demand.

The predecessor VMT forecasting model was developed following an assessment of the alternative models described below. While both fleet-based and driver-based systems have appealing characteristics and are useful under certain modeling conditions, the latter of these approaches was considered to be most appropriate to the needs of the model. This is because the fleet-based approach relies to a greater degree on the continuation of past trends, and cannot explicitly address many of the underlying factors that may lead to shifts in VMT growth patterns in the future, while a driver-based approach allows explicit modeling of the factors that may "bend the curve", such as the aging of the population.

A driver-based approach takes the following form:

$$\mathbf{VMT_{Total}} = \left(\frac{\mathbf{VMT}}{\mathbf{Licensed\ Driver}}\right)\left(\frac{\mathbf{Licensed\ Drivers}}{\mathbf{Driving\ Age\ Population}}\right)\mathbf{(Driving\ Age\ Population)}$$

Forecasting two of the three terms of this equation is relatively straightforward. A forecast of

the driving-age population is provided by the Census Bureau,[13] and licensure rates for most segments of the population are rapidly approaching unity. Therefore the principal task is to accurately forecast VMT per driver.

The functional form chosen to forecast VMT per driver in the *1992 Annual Energy Outlook (AEO92)* is an incremental modification of the econometric model used in the *AEO91*. Due to the limited (20 year) forecast period, it was convenient and defensible to consider society's demographic structure to be relatively static and uninfluential over trends which may be effectively characterized in the aggregate by economic variables. In a longer term forecast, however, projections of economic variables and the population's responses to them become more ambiguous, whereas the effects of gradual demographic change are expected to become more pronounced. This revised model, presented below, has been considered an interim step in the development of a longer term model which is more sensitive to structural change:

$$\mathbf{LnVMTPC} = \alpha + \beta_1(\mathbf{LnCPM}) + \beta_2(\mathbf{LnYPC}) + \beta_3(\mathbf{Ln}(N_{20}/N_{65}))$$

where:

VMTPC = VMT per driving age population.
CPM = Average fuel cost per mile of driving, expressed in 1982 dollars.
YPC = Income per capita, expressed in 1982 dollars.
N_{20}, N_{65} = The population between the ages of 20-29 and older than 65, respectively.

This model replaced a previous VMT forecasting model in which fuel price and disposable income were the only factors influencing the growth of VMT. One consequence of that formulation was that per capita driving rates were forecast to grow without moderation—an issue that the inclusion of the demographic parameter was designed to address.

This specification was based on the notion that the rate of growth of per capita VMT should decline over time, as the population ages. The use of the ratio of the number of twenty to twenty nine year-olds to the number of those over the typical retirement age of sixty-five was an attempt to characterize the changing demographic structure of society. This ratio has been forecast to decline over the forecast period, and served to moderate the growth of VMT without constraining its trend to an *a priori* limit. In summary, this model placed a moderate demographic constraint on VMT growth, while using the same price and income regressors as were employed in the 1991 AEO. This constraint lowered the near-term VMT forecast without resorting to the artifice of

[13] *Projections of the Population of the United States, by Age, Sex, and Race: 1988 to 2080*, U.S. Department of Commerce, Bureau of the Census, Current Population Reports Series P-25, No. 1018 (Jan. 1989).

imposing *ad hoc* limits to growth. This model, however, was somewhat compromised by the rudimentary demographic influence and by the absence of effects rising from changing female driving patterns. The VMT model implemented in NEMS has been designed to address these concerns.

ALTERNATIVE SPECIFICATIONS

The projection of VMT is rarely an end in itself; levels of personal travel demand are generally used as an intermediate step in the estimation of various factors which are influenced by driving levels. The following pages briefly describe several VMT forecasting methods currently being used by various agencies, and were considered in the development of the NEMS VMT forecasting model. The form that each model takes is a reflection of the concerns of the commissioning agency, the purpose to which the model is to be put, the time scale of the forecast, the availability of adequate data, and the preconceptions of the model designers.

The models described below are representative of the following three basic forecasting approaches typically used to project VMT. The *fleet-based* approach, which uses estimates of the distances driven by each vehicle, disaggregated by vintage, and linear projections of vehicle stock to project total VMT in a given year, is useful in predicting fuel consumption and pollutant emissions. Secondly, the *demographic* approach combines estimates of distances driven by each driver, disaggregated by age, and age-stratified population projections to determine VMT. This is a simple method which relies on projections made from readily available data, but which may be affected by overlooked economic or regional factors. Finally, the *economic* approach uses estimates of vehicle operating cost and other economic parameters such as personal income as predictive variables. Such approaches are commonly used for national-level forecasting, and have a high explanatory power. However, their reliance on forecasts of economic variables and the neglect of potential saturation effects renders such models relatively unstable in the mid- to long-term.

A fourth approach to VMT forecasting, *trip generation*, is a site-specific method which involves forecasting the number of trips taken, and predicting destinations, travel modes, and routes. This is a data intensive approach which is typically used on a local or regional level to predict road congestion and demand for mass transit, and was not considered to be commensurate with the requirements of NEMS.

FHWA/Faucett VMT Forecasting Model: FHWA, and DOT in general, uses this model designed by Jack Faucett Associates. The model is a generalized difference equation, using a log-linear

econometric form, which consolidates the previous models used by the Department of Transportation. It is designed for both short and long range forecasting of VMT and vehicle stock on a national level for five categories of vehicle: personal use vehicles and four separate truck categories. The growth rate for VMT is estimated to be constrained by fuel price increases, forecast to begin in 1987 and continue at an increasing rate; and a tapering off in the expected rate of increase in the number of driver licenses per thousand population.

The forecasting model for personal-use vehicles used by FHWA takes the following form:

$$\begin{aligned} \mathbf{LVMTPUPC}_t = \alpha \; & + \rho \mathbf{LVMTPUPC}_{t-1} + \beta_1(\mathbf{LPIPC}_t - \rho \mathbf{LPIPC}_{t-1}) \\ & + \beta_2(\mathbf{LTCXDP}_t - \rho \mathbf{LTCXDP}_{t-1}) \\ & + \beta_3(\mathbf{LDLPK}_t - \rho \mathbf{LDLPK}_{t-1}) \\ & + \beta_4(\mathbf{FSD}_t - \rho \mathbf{FSD}_{t-1}) \end{aligned}$$

where:

LVMTPUPC = Log of personal-use VMT per capita
LPIPC = Log of personal income per capita
LTCXDP = Log of vehicle operating cost index deflated by CPI[14]
LDLPK = Log of number of driver licenses per thousand population
FSD = Fuel shortage dummy[15]
ρ = The lag factor, set to 0.6017

The primary constraint in an econometric approach is the increasing uncertainty of price and macroeconomic projections in the mid- to long-term. The sensitivity of the model to fluctuations in these variables serves to increase the uncertainty of the projection towards the end of the forecast period.

MOBILE4 Fuel Consumption Model (EPA): While most models used by EPA concentrate on the local or regional level, its fuel consumption model makes forecasts of nationwide VMT. The MOBILE4 Fuel Consumption Model (M4FC) is used by EPA's Office of Mobile Sources in conjunction with its MOBILE4 Emissions Model to estimate individual states' degree of attainment of ambient air standards. M4FC is a fleet-based model which uses linear projections of vehicle stocks by type, subsequently estimating miles per year according to type and vintage. There are few demographic influences in the model. VMT in this model is estimated using

[14] The operating cost index comprises a weighted average of fuel costs, fuel efficiency forecasts, maintenance costs, the purchase price of new vehicles, and an assumed forecast of real increases in the cost of insurance.

[15] The fuel shortage dummy is set to zero, but is included to test, at the option of the user, the impact of an abnormal disruption in fuel supplies.

vehicle stock projections, age distributions, and mileage accumulation rates as follows:[16]

$$VMT_{TOTAL} = \sum_{Age}\left(\frac{VMT}{Vehicle}\right)_{Age} * (\%\ of\ Vehicles)_{Age} * (Total\ Vehicles)$$

Although a stock-based model can provide a more robust extended forecast than one based solely on econometric methods, there remain concerns about such a model's sensitivity to deviations from vehicle purchase and scrappage-rate assumptions. These assumptions are predicated on expectations concerning consumer behavior and technological innovation, which are not easily projectable. The M4FC model is a revision of an earlier model, M3FC, and incorporates factors which attempt to reflect society's evolving driving patterns, assuming, somewhat optimistically, the eventual congruence of male and female driving characteristics.

The Consumer Automotive Response Model (CAR): This transportation model, which is used by the EPA Policy Office, may be distinguished from that used by the Office of Mobile Sources by its ultimate purpose. While the MOBILE4 model uses a fleet-based approach to estimate emissions of specific pollutants, the model used by the policy office takes an econometric approach to forecast the effects of various policy options such as the impact of a gas tax on VMT, and consequently, on criterion pollutant emissions.

The CAR model is a discrete-choice, logit model which is based on Kenneth Train's Consumer Choice Model which was originally prepared for the California Energy Commission. It comprises a system of submodels which separately forecast vehicle ownership and stock characteristics, and miles traveled in each vehicle at the household level. The personal travel portion of Train's model forecasts VMT in four categories: intra- and inter-city work and non-work travel, using the following log-linear econometric form:

$$Log(VMT) = \beta Z$$

where β and Z are vectors of parameters and explanatory variables, respectively.[17] These explanatory variables include logarithms of the household income and size; the operating cost of each vehicle, in cents per mile; the number of workers in the household; the number of transit trips per capita in the area in question; and several dummy variables identifying the urban density

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[16] Information on the MOBILE3 and MOBILE4 Fuel Consumption Models have been obtained through conversations with Phil Lorang and Mark Wolcott of EPA's Emissions Control Division, and from *Forecasting Vehicle Miles Traveled and Other Variables That Affect Mobile-source Emissions*, prepared for EPA by RCG/Hagler, Bailly, Inc., 8/18/88.

[17] From K. Train, *Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand*, 1986, Chapter 8.

and geographic region of the household. The operating cost of each vehicle is further considered to be an endogenous variable, as it is implicitly defined by each household's purchase decision. This parameter is therefore determined by a variety of exogenous demographic variables such as the age, sex, and education level of the household head; the regional gas price and the commuting distance.

This model represents a rather detailed merging of econometric and demographic approaches to forecasting. It is a relatively complex model, involving the independent forecasting of a large number of exogenous variables. The descriptive ability of the original Consumer Choice model does not appear to be enhanced by its level of detail, however, as the R-squared of 0.114 for the one-vehicle household submodel does not explain a significant level of variation in the data.[18] A demographic model which is sensitive to economic conditions, but at a lower level of complexity may provide the basis for a credible long-term VMT forecast.

Transportation Energy and Emissions Modeling System (TEEMS): Developed by Argonne National Laboratory, TEEMS is a series of disaggregate models, linked to produce forecasts of transportation activity and energy demand. The models cover both freight and passenger transport, with personal and fleet vehicles being separately addressed.

This is a combination demographic and stock model, based on forecasts of distributions of household characteristics. It is based on Kenneth Train's Consumer Choice Model, and depends on changes in the distribution of the sample of households, not on average characteristics. In the section which determines an estimate of personal travel, a matrix is constructed using data from the 1983 Nationwide Personal Transportation Study (NPTS), which is then adjusted to represent 1985 conditions.[19] The VMT estimate is calculated as follows:

$$\mathbf{VMT}_{\mathbf{Total}} = \sum_{\mathbf{Cell=1}}^{\mathbf{N}} \left(\frac{\mathbf{VMT}}{\mathbf{Vehicle}}\right)_{\mathbf{Cell}} \left(\frac{\mathbf{Vehicles}}{\mathbf{Household}}\right)_{\mathbf{Cell}} (\mathbf{Households})_{\mathbf{Cell}}$$

The survey sample is stratified into cells according to the following six household attributes:

1. Location (three categories)
2. Income (four categories)
3. Age of Householder (four categories)

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[18] K. Train, *op. cit.*, p. 165.

[19] For a detailed description of TEEMS, see: Mintz, M.M., and Vyas, A.D., *Forecast of Transportation Energy Demand Through the Year 2010*, Argonne National Laboratory Report, ANL/ESD-9, April 1991.

4. Household Size (four categories)
5. Number of Drivers (four categories)
6. Number of Vehicles (four categories)

Distributions of households by demographic attribute are independently forecast, and the occupancy of each cell in the future is estimated. This model contains elements of all three of the considered model types, but is primarily a stock model with a pronounced demographic influence. The stratified approach to forecasting is useful, in that it provides for the consideration of selected discrete characteristics, permitting an evaluation based on particular, quantifiable attributes.

Two dangers of this approach lie in specifying a broader stratification scheme than can be supported by the available sample, resulting in underpopulated levels; and the potential for the disproportionate influence of extreme data. As mentioned above, this model's reliance on vehicle purchase and scrappage projections, as well as its assumption of a static distribution of VMT per vehicle may have to be revised in order to use the model for forecasts extending several decades. This model also requires the independent forecast of a large number of exogenous inputs, consequently increasing the likelihood of significant impacts from the propagation of errors.

FHWA Spreadsheet Forecast: This model was developed on a spreadsheet system for the Federal Highway Administration. It was used by FHWA in 1987 to produce a series of forecasts of automobile and light truck VMT through the year 2000. It represents the base case in a series of forecasts produced by FHWA in 1987.[20] This is a straightforward demographic model, using disaggregated population data to project VMT. For inputs it relies on data from the 1969, 1977, and 1983 NPTS data bases, and population projections from the Census Bureau. The model also forecasts the total number of drivers, the VMT per driver, and the fraction of the driving age population with driver licenses from 1985 to 2020. These figures are also dependent on assumptions of a static distribution of driver licenses across the various age groups. The model forecasts total VMT by sex as follows:

$$\mathbf{VMT}_{\mathbf{TOTAL}} = \sum_{\mathbf{AGE}} \left(\frac{\mathbf{VMT}}{\mathbf{Capita}}\right)_{\mathbf{AGE}} * (\mathbf{Population})_{\mathbf{AGE}}$$

This model has the benefit of simplicity, relying on very few inputs. Two of these, population and licensure rates, can be considered robustly forecastable. The "most likely" case of the model,

[20] The Future National Highway Program: 1991 and Beyond, Working Paper No. 2, *Trends and Forecasts of Highway Passenger Travel*, FHWA, 12/87.

however, assumes unlimited VMT per capita growth at constant rates, and a female/male driving ratio of 60 percent, both of which are subject to question. The incorporation of economic dependencies in such a demographic model could provide opportunities for analysis of the impact of various policy initiatives on VMT.

MODEL STRUCTURE

In developing the current VMT model, it has been necessary to address data quality and functional specification issues. In order to make the new model consistent with the NEMS requirements, economic variables (driving cost per mile and disposable personal income per capita) have been transformed so that values are expressed in 1987 dollars rather than 1982 dollars. The demographic variable previously used (population between the ages of 20 and 29 divided by population over 65) has been removed from the specification and other demographic variables have been incorporated.

Several functional forms were tested in the development of this model, bringing to light the difficulty in constructing a model which incorporates both economic and demographic parameters which may be used for forecasting in the mid- to long-term. Problems with autocorrelation and multicollinearity motivated the implementation of a two stage approach in which the results of a linear econometric model are adjusted to reflect demographic constraints. The first stage provides a forecast of per capita VMT, based on historical data, which assumes that the age profile of the country remains constant. The second stage imposes a limiting factor which reflects the projected aging of the population and the reduced driving rates associated with older drivers.

In the first stage of this model, a generalized difference equation is used to estimate the unadjusted VMT per capita:[21]

$$\begin{aligned} VMTPC_T = {} & \rho\, VMTPC_{T-1} + 0.28(1-\rho) - 7.50(CPM87_T - \rho\, CPM87_{T-1}) \\ & + 3.6\times10^{-4}(YPC87_T - \rho\, YPC87_{T-1}) + 8.36(PrFem_T - \rho\, PrFem_{T-1}) \end{aligned} \qquad (81)$$

where:

VMTPC = the vehicle miles traveled per capita
CPM87 = the fuel cost of driving a mile, expressed in 1987 dollars.
YPC87 = the disposable personal income per capita, expressed in 1987 dollars.
PrFem = the ratio of per capita female driving to per capita male driving.
ρ = the lag factor, estimated using the Cochrane-Orcutt iterative procedure to be 0.72.

[21] VMT per capita should be understood mean VMT per population 16 years and older. "Per capita" is used for simplicity. Its use in other variables refers to the total US population.

In the second stage, the unadjusted forecast is modified by a demographic adjustment factor (DAF). This is an index which is based on projections of the proportion of the population of 60 years of age (P>60) and the expected ratio of per capita driving by those over 60 to those under 60 (PVMT60), and is set to 1.0 in 1990.

$$DAF = 1 - [P>60] \cdot (1 - PVMT60_T)] \qquad (82)$$

$$ADJVMTPC_T = VMTPC_T \cdot DAF_T$$

where:

DAF = the demographic adjustment facto

ADJVMT= adjusted vehicle miles traveled per capita

The adjusted VMT per capita is subsequently converted to total VMT by multiplying by the population at or above the driving age of 16 years. Total demand for light duty vehicle travel is finally allocated among the various conventional and alternative automobile technologies considered in NEMS, and consumptions estimates are generated for each type of fuel.

Figure 3B-2. LDV Stock Module 1: Process New Additions to LDV Stock

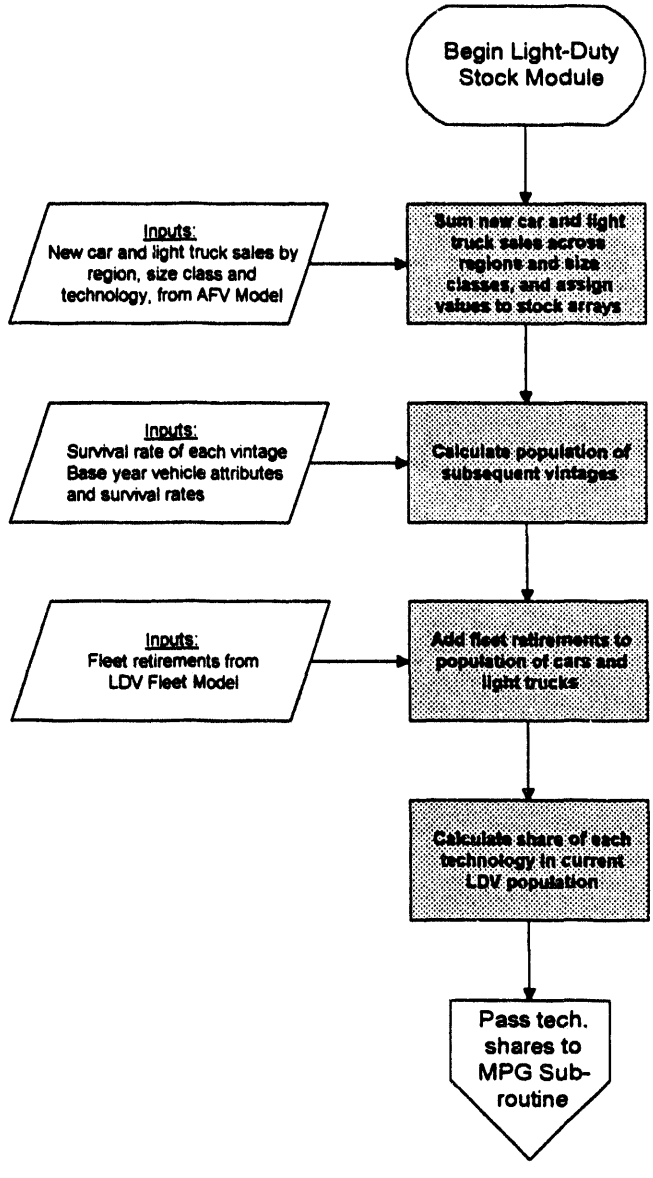


Figure 3B-3. LDV Stock Module 2: Determine Characteristics of Current LDV Stock

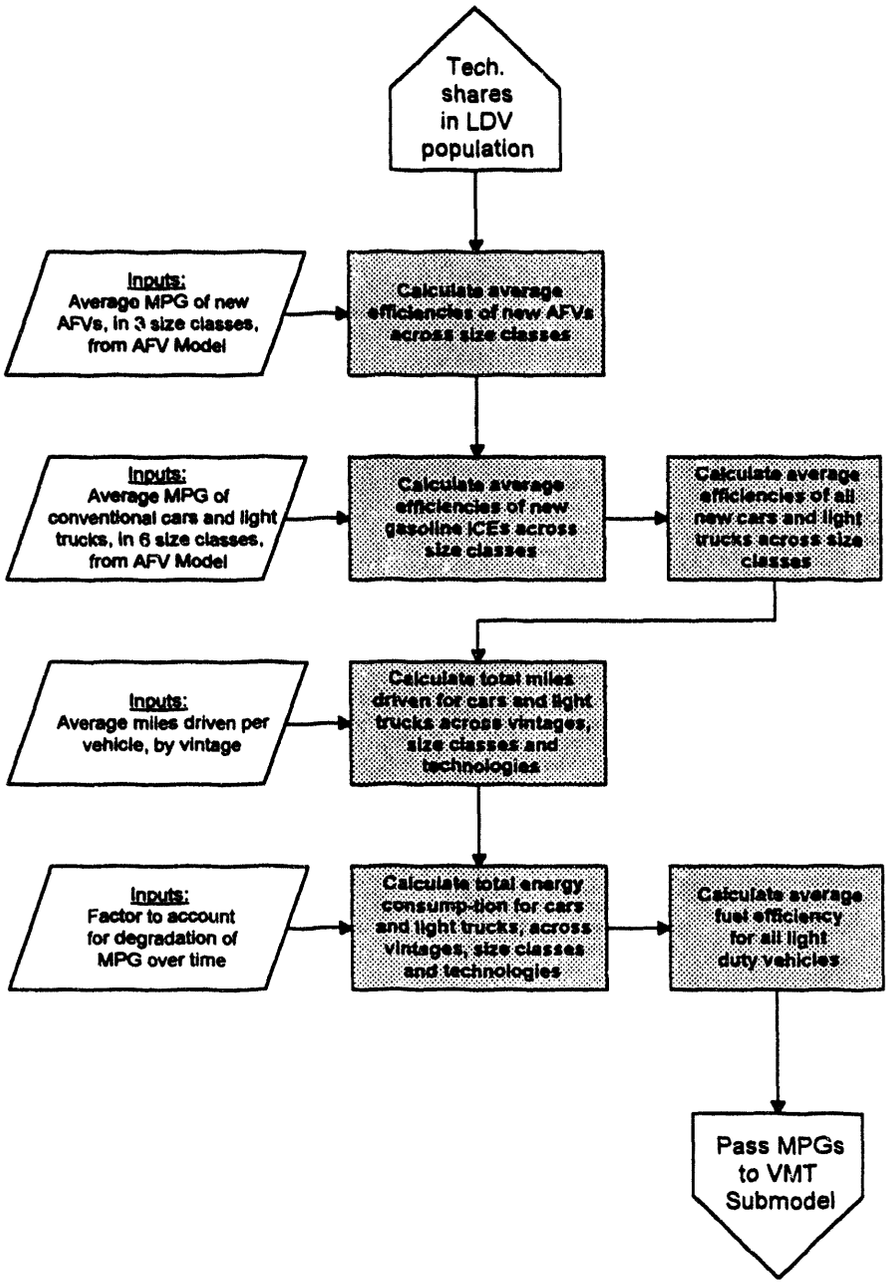
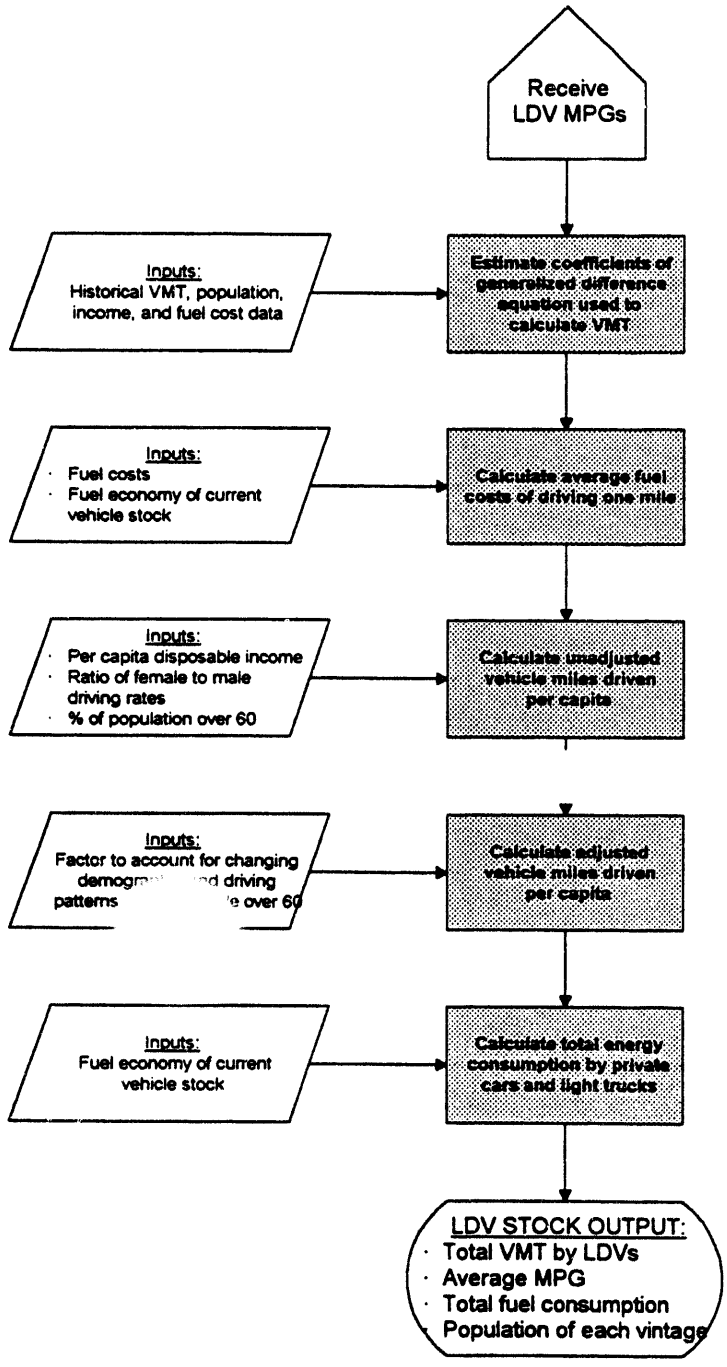


Figure 3B-4. LDV Stock Module 3: Vehicle Miles Traveled Model



3C. LDV Fleet Module

The Light Duty Vehicle Fleet Module generates estimates of the stock of cars and trucks used in business, government, and utility fleets. The model also estimates travel demand, fuel efficiency, and energy consumption by these fleet vehicles prior to their transition to the private sector at predetermined vintages.

RATIONALE

Fleet Vehicles are treated separately in TRAN because of the special characteristics of fleet light duty vehicles. The LDV Fleet Module generates estimates of the stock of cars and light trucks which are used in three different types of flees, as well as VMT, fuel efficiency and energy consumption estimates which are distinct from those generated for personal light duty vehicles in the LDV and LDV Stock Modules. The primary purpose for this was not only to simulate as accurately as possible the very different sets of characteristics one would expect to see in fleet as opposed to personal vehicles but also to allow for the greater opportunity for regulaton and policy-making that fleet purchases represent. Legislative mandates for AFV purchases, fleet fuel efficiencies, etc. can be incorporated through the subroutine TLEGIS, which has been set up specifically for this purpose.

ALTERNATIVE SPECIFICATIONS

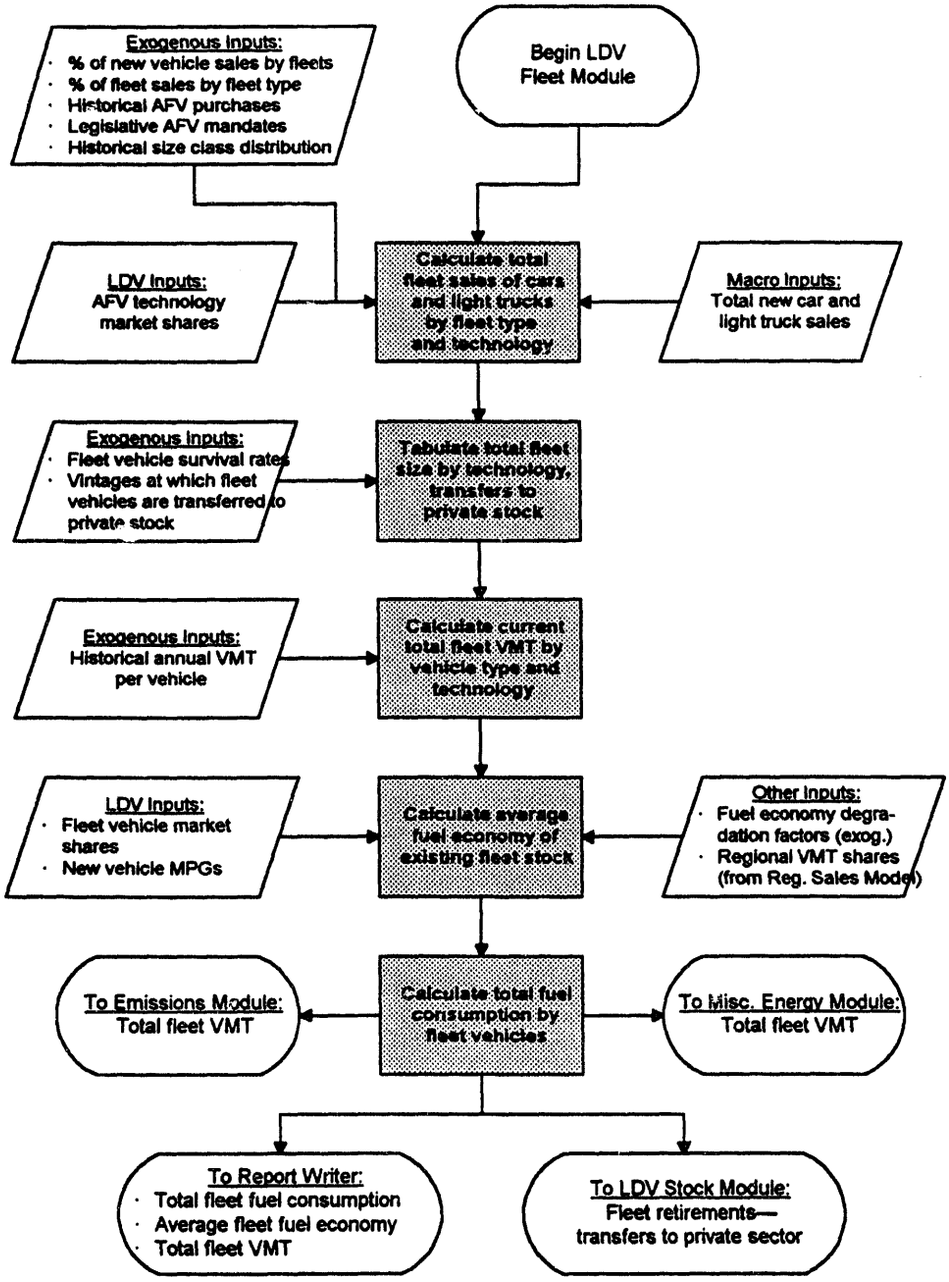
No alternative specifications were considered.

MODEL STRUCTURE

In a departure from the conventions of other modules, this model uses the same variable names for cars and light trucks; they are distinguished by the value of an index designating vehicle type. Vehicles are also distinguished by the type of fleet to which they are assigned; business, government, and utility fleets are assumed to have different operating characteristics and retirement rates. This model consists of three stages: determine total surviving fleet stocks and travel demand, calculate the fuel efficiency of fleet vehicles, and estimate the consequent fuel consumption.

The flowchart for the Light Duty Vehicle Fleet Module is presented below in Figure 3C-1. Additional flowcharts outlining major LDV Fleet calculations in more detail are presented at the end of this section.

Figure 3C-1. Light Duty Vehicle Fleet Module



Calculate Fleet Stocks and VMT

Calculate fleet acquisitions of cars and light trucks:

$$FLTSAL_{VT=1,ITY,T} = FLTCRAT * SQTRCARS_T * FLTCSHR_{ITY}$$

$$\text{and:} \tag{81}$$

$$FLTSAL_{VT=2,ITY,T} = FLTTRAT * SQDTRUCKSL_T * FLTTSHR_{ITY}$$

where:

FLTSAL = Sales to fleets by vehicle and fleet type
FLTCRAT = Fraction of total car sales attributed to fleets
FLTTRAT = Fraction of total truck sales attributed to fleets
SQTRCARS = Total automobile sales in a given year
SQDTRUCKSL = Total light truck sales in a given year
FLTCSHR = Fraction of fleet cars purchased by a given fleet type
FLTTSHR = Fraction of fleet trucks purchased by a given fleet type
VT = Index of vehicle type: 1 = cars, 2 = light trucks
ITY = Index of fleet type: 1 = business, 2 = government, 3 = utility

Determine total alternative fuel fleet vehicle sales, using either the market-driven or legislatively mandated values :

$$FLTALT_{VT,ITY,T} = MAX\left[\left(FLTSAL_{VT,ITY,T} * FLTAPSHR1_{ITY}\right), EPACT_{VT,ITY,T}\right] \tag{82}$$

where:

FLTALT = Number of AFV's purchased by each fleet type in a given year
FLTAPSHR1 = Fraction of each fleets' purchases which are AFV's, from historical data
EPACT = Legislative mandates for AFV purchases, by fleet type

The difference between total and AFV sales represents conventional sales:

$$FLTCONV_{VT,ITY,T} = FLTSAL_{VT,ITY,T} - FLTALT_{VT,ITY,T} \tag{83}$$

where:

FLTCONV = Fleet purchases of conventional vehicles
FLTSAL = Sales to fleets by vehicle and fleet type
FLTALT = Number of AFV's purchased by each fleet type in a given year

Fleet purchases are subsequently divided by size class:

$$FLTSLSCA_{VT,ITY,IS,T} = FLTALT_{VT,ITY,T} * FLTSSHR_{VT,ITY,IS}$$

and: (84)

$$FLTSLSCC_{VT,ITY,IS,T} = FLTCONV_{VT,ITY,T} * FLTSSHR_{VT,ITY,IS}$$

where:

FLTSLSCA = Fleet purchases of AFV's, by size class
FLTSLSCC = Fleet purchases of conventional vehicles, by size class
FLTSSHR = Percentage of fleet vehicles in each size class, from historical data
IS = Index of size classes: 1 = small, 2 = medium, 3 = large

A new variable is then established, disaggregating AFV sales by engine technology:

$$FLTECHSAL_{VT,ITY=1,IS,ITECH} = FLTSLSCA_{VT,ITY=1,IS} * APSHRFLTB_{VT,ITECH,ITY=1}$$

$$FLTECHSAL_{VT,ITY=1,IS,ITECH} = FLTSLSCA_{VT,ITY=1,IS} * FLTECHSHR_{ITECH,ITY} \quad (85)$$

and:

$$FLTECHSAL_{VT,ITY,IS,ITECH=6} = FLTSLSCC_{VT,ITY,IS}$$

where:

FLTECHSAL = Fleet sales by size, technology, and fleet type
APSHRFLTB = Alternative technology shares for the business fleet
FLTECHSHR = Alternative technology shares for the government and utility fleets
ITECH = Index of engine technologies: 1-5 = alternative fuels (neat), 6 = gasoline

Sales are then summed across size classes:

$$FLTECH_{VT,ITY,ITECH} = \sum_{IS=1}^{3} FLTECHSAL_{VT,ITY,IS,ITECH} \quad (86)$$

where:

FLTECH = Vehicle purchases by fleet type and technology

The next step is to modify the array of surviving fleet stocks from previous years, and to add these new acquisitions. This is done by applying the appropriate survival factors to the current vintages and inserting FLTECH into the most recent vintage:

$$FLTSTKVN_{VT,ITY,ITECH,IVINT,T} = FLTSTKVN_{VT,ITY,ITECH,IVINT-1,T-1} * SURVFLTT_{VT,IVINT-1}$$

and: (87)

$$FLTSTKVN_{VT,ITY,ITECH,IVINT=1,T} = FLTECH_{VT,ITY,ITECH,T}$$

where:

FLTSTKVN = Fleet stock by fleet type, technology, and vintage
SURVFLTT = Survival rate of a given vintage
IVINT = Index referring to vintage of fleet vehicles

The stocks of fleet vehicles of a given vintage are then identified, assigned to another variable, and removed from the fleet:

$$\mathbf{OLDFSTK}_{VT,ITY,ITECH,IVINT,T} = \mathbf{FLTSTKVN}_{VT,ITY,ITECH,IVINT,T} \quad (88)$$

where:

OLDFSTK = Old fleet stocks of given types and vintages, transferred to the private sector

The variable OLDFSTK is subsequently sent to the LDV Stock Model to augment the fleet of private vehicles. The vintages at which these transitions are made are dependent on the type of vehicle and the type of fleet, as shown below.

Vehicle Type (VT)	Fleet Type (ITY)	Transfer Vintage (IVINT)
Automobile (VT = 1)	Business (ITY = 1)	5 Years
Automobile	Government (ITY = 2)	6
Automobile	Utility (ITY = 3)	7
Light Truck (VT = 2)	Business	6
Light Truck	Government	7
Light Truck	Utility	6

Total surviving vehicles are then summed across vintages:

$$\mathbf{TFLTECHSTK}_{VT,ITY,ITECH,T} = \sum_{IVIN=1}^{6} \mathbf{FLTSTKVN}_{VT,ITY,ITECH,IVIN,T} \quad (89)$$

where:

TFLTECHSTK = Total stock within each technology and fleet type

The percentage of total fleet stock represented by each of the vehicle types and technologies is determined as follows:

$$VFSTKPF_{VT,ITY,ITECH,T} = \frac{TFLTECHSTK_{VT,ITY,ITECH,T}}{\sum_{VT=1}^{2}\sum_{ITY=1}^{3}\sum_{ITECH=1}^{6} TFLTECHSTK_{VT,ITY,ITECH,T}} \quad (90)$$

where:

VFSTKPF = Share of fleet stock by vehicle type and technology

Historical data on the amount of travel by fleet vehicles is now used to estimate total fleet VMT:

$$FLTVMT_T = \sum_{VT=1}^{2}\sum_{ITY=1}^{3}\sum_{ITECH=1}^{6} \left(TFLTECHSTK_{VT,ITY,ITECH,T} * FLTVMTYR_{VT,ITY,T}\right) \quad (91)$$

where:

FLTVMT = Total VMT driven by fleet vehicles

FLTVMTYR = Annual miles of travel per vehicle, by vehicle and fleet type

Total VMT is then disaggregated by vehicle type and technology:

$$FLTVMTECH_{VT,ITY,ITECH,T} = FLTVMT_T * VFSTKPF_{VT,ITY,ITECH,T} \quad (92)$$

where:

FLTVMTECH = Fleet VMT by technology, vehicle type, and fleet type

Calculate Fleet Stock MPG

The average efficiencies of the five non-gasoline technologies are calculated as follows:

$$FLTMPG_{VT=1,ITY,ITECH} = \left[\sum_{ASC=1}^{3} \frac{FMSHC_{ITY,ITECH,ASC}}{NAMPG_{ITS,ASC}}\right]^{-1}$$

and: (93)

$$FLTMPG_{VT=2,ITY,ITECH} = \left[\sum_{ASC=1}^{3} \frac{FMSHLT_{ITY,ITECH,ASC}}{NAMPG_{ITS,ASC} * RATIO_{ASC}}\right]^{-1}$$

where:

FLTMPG = New fleet vehicle fuel efficiency, by fleet type and engine technology

FMSHC = The market share of fleet cars, from the AFV model

FMSHLT = The market share of fleet light trucks, from the AFV model

NAMPG = New AFV fuel efficiency, from the AFV model

ITS = Index which matches technologies in the AFV model to corresponding *ITECH*

For conventional technologies, when *ITECH* refers to gasoline ICE's, the calculation is similar. FEM estimates of fuel economy for the six vehicle size classes are averaged into three classes to correspond to the output of the fleet model, and new fleet vehicle fuel economy is calculated as follows:

$$\mathbf{FLTMPG}_{VT=1,ITY,ITECH} = \left[\sum_{ASC=1}^{3} \frac{\mathbf{FMSHC}_{ITY,ITECH,ASC}}{\mathbf{FEC3SC}_{ASC}} \right]^{-1}$$

and: **(94)**

$$\mathbf{FLTMPG}_{VT=2,ITY,ITECH} = \left[\sum_{ASC=1}^{3} \frac{\mathbf{FMSHLT}_{ITY,ITECH,ASC}}{\mathbf{FET3SC}_{ASC}} \right]^{-1}$$

where:

FEC3SC = New car MPG, in three size classes, from the FEM model
FET3SC = New light truck MPG, in three size classes, from the FEM model

The fuel efficiency of new vehicles is then added to an array of fleet stock efficiencies by vintage, which is adjusted to reflect the passage of time:

$$\mathbf{MPGFSTK}_{VT,ITY,ITECH,IVIN,T} = \mathbf{MPGFSTK}_{VT,ITY,ITECH,IVIN-1,T-1}$$

and: **(95)**

$$\mathbf{MPGFSTK}_{VY,ITY,ITECH,IVIN=1,T} = \mathbf{FLTMPG}_{VT,ITY,ITECH,T}$$

where:

MPGFSTK = Fleet MPG by vehicle and fleet type, technology, and vintage

Average fuel efficiency by vehicle and fleet type is then calculated:

$$\mathbf{MPGFLTSTK}_{VT,ITY,ITECH} = \left[\sum_{IVINT=1}^{MAXVINT} \frac{\left(\dfrac{\mathbf{FLTSKTVN}_{VT,ITY,ITECH,IVINT}}{\mathbf{MPGFSTK}_{VT,ITY,ITECH,IVINT} * \mathbf{VDF}_{VT}} \right)}{\left(\mathbf{TFLTECHSTK}_{VT,ITY,ITECH} \right)} \right]^{-1} \quad \textbf{(96)}$$

where:

MPGFLTSTK = Fleet MPG by vehicle and fleet type, and technology, across vintages
MAXVINT = Maximum *IVIN* index associated with a given vehicle and fleet type

The overall fleet average MPG is finally calculated for cars and light trucks:

$$FLTTOTMPG_{VT,T} = \left[\sum_{ITY=1}^{3} \sum_{ITECH=1}^{8} \frac{VFSTKPF_{VT,ITY,ITECH,T}}{MPGFLTSTK_{VT,ITY,ITECH,T}} \right]^{-1} \quad (97)$$

where:

FLTTOTMPG = Fleet vehicle average fuel efficiency for cars and light trucks

Calculate Fuel Consumption by Fleet Vehicles

Fuel consumption is simply the quotient of fleet travel demand and fuel efficiency, which have been addressed above:

$$FLTLDVC_{VT,ITY,ITECH,T} = \frac{FLTVMTECH_{VT,ITY,ITECH,T}}{MPGFLTSTK_{VT,ITY,ITECH,T}} \quad (98)$$

where:

FLTLDVC = Fuel consumption by technology, vehicle and fleet type

Consumption is then summed across fleet types, and converted to Btu values:

$$FLTFCBTU_{VT,ITECH,T} = \sum_{ITY=1}^{3} FLTLDVC_{VT,ITY,ITECH,T} * QBTU_{ITECH} \quad (99)$$

where:

FLTFCBTU = Fuel consumption, in Btu, by vehicle type and technology
QBTU = Energy content, in Btu/Gal, of the fuel associated with each technology

Consumption by trucks and cars are added, and total consumption is subsequently divided among regions:

$$FLTFCBTUR_{IR,ITECH,T} = \sum_{VT=1}^{2} FLTFCBTU_{VT,ITECH,T} * RSHR_{IR,T} \quad (100)$$

where:

FLTFCBTUR = Regional fuel consumption by fleet vehicles, by technology
RSHR = Regional VMT shares, from the Regional Sales Model
IR = Index of regions

Figure 3C-2: LDV Fleet Module 1: Process New Fleet Acquisitions

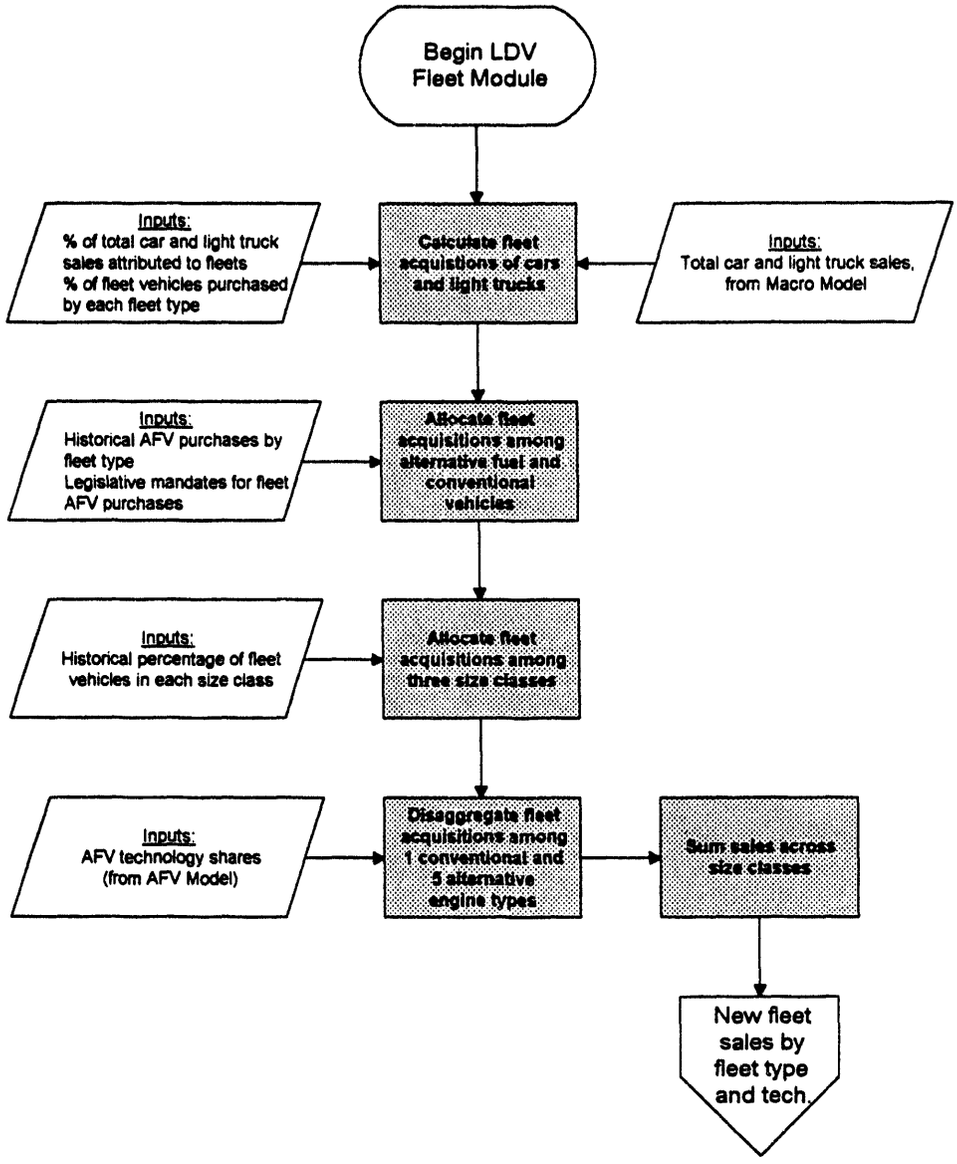


Figure 3C-3. LDV Fleet Module 2: Determine Characteristics of Existing Fleets

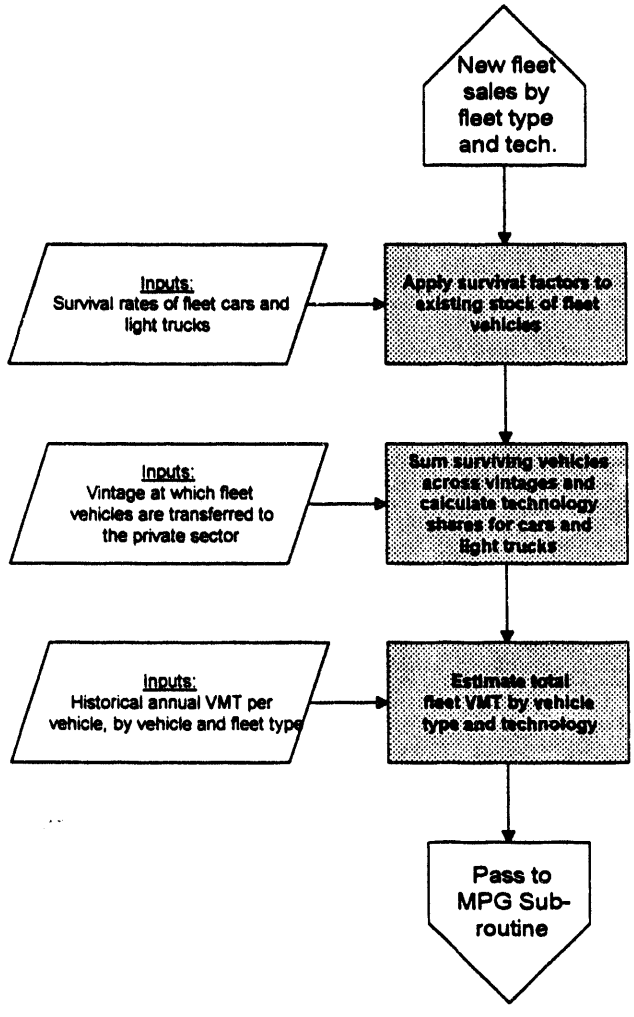
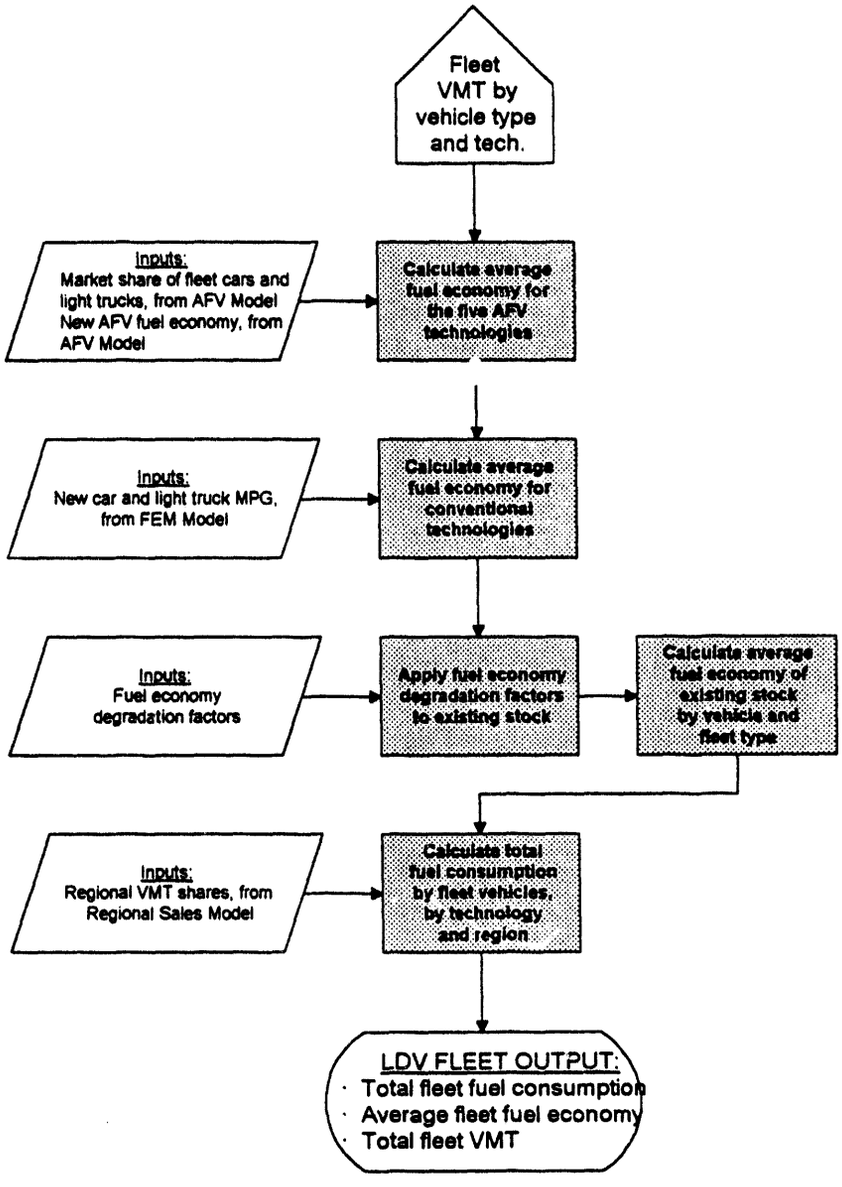


Figure 3C-4. LDV Fleet Module 3: Determine Fleet Fuel Economy and Consumption



3D. Air Travel Module

The air travel component of the NEMS Transportation Model comprises two separate submodels: the Air Travel Demand Model and the Aircraft Fleet Efficiency Model. These models use NEMS forecasts of fuel price, macroeconomic activity, and population growth, as well as assumptions about aircraft retirement rates and technological improvements to generate forecasts of passenger and freight travel demand and the fuel required to meet that demand.

3D-1. Air Travel Demand Model

RATIONALE

The Air Travel Demand Model produces forecasts of passenger travel demand, expressed in revenue passenger-miles (RPM), and air freight demand, measured in revenue ton-miles (RTM). These are combined into a single demand for available seat-miles (ASM), and passed to the Aircraft Fleet Efficiency Model, which adjusts aircraft stocks in order to meet that demand.

Structural changes in the airline industry over the past decade have made it difficult to develop long-term forecasts of travel demand. The opening-up of routes, the implementation of the "hubbing" system, the use of competitive pricing, and the growth of a dedicated air freight system are just some of the consequences of a deregulated market. The commercial aviation system is still in a state of flux, having yet to settle down to the level of long-run equilibrium necessary for the application of conventional forecasting methodologies. Today, aviation forecasting experts are emphasizing the role of "judgement" in planning for the future—an implicit acknowledgement of the limitations of a purely quantitative methodology.[22] It is with this in mind that a policy-sensitive approach to forecasting air travel demand has been developed.

In order to increase the sensitivity of the forecast to economic and demographic parameters, a disaggregate model, incorporating separate treatment of business, personal, and international passenger travel has been implemented. Separate forecasts of domestic passenger and freight travel are generated, influenced by economic, demographic and fuel price factors, and are combined into an aggregate estimate of air travel demand. This model stands in contrast to its predecessor, used in producing the 1993 AEO, in which an aggregate demand for commercial passenger travel is first estimated using a constant-elasticity approach:

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[22] *Aviation Forecasting Methodology*, Transportation Research Circular No. 348, Transportation Research Board, Washington, D.C., 8/89, p. 8.

$$RPM_T = 1.2566 \cdot RPM_{1985} \left(\frac{\text{Real GNP}_T}{\text{Real GNP}_{1985}} \right)^{1.92} \left(\frac{\text{TicketPrice}_T}{\text{TicketPrice}_{1985}} \right)^{-0.413}$$

The RPMs thus generated are subsequently incremented by a fixed percentage representing demand by general aviation and dedicated air cargo aircraft, and a constant military demand. That model's lack of sensitivity to economic and demographic influences has necessitated the consequent revision.

The Air Travel Demand Model is based on several assumptions about personal behavior and the structure of the airline industry. Of greatest significance is the assumption that the deregulation of the industry has substantially altered the dynamics of passenger travel; model parameters have therefore been estimated using only post-deregulation data. It is further assumed that business and personal travel are motivated by different measures of economic conditions, and should be modeled separately. Finally, it is assumed that personal travel demand is influenced by demographic conditions, and forecasts of this demand should be adjusted to reflect the changing age and gender characteristics of the U.S. population. The design of this model, and its underlying assumptions have been influenced by several literature sources and alternative model specifications which are described below.

ALTERNATIVE SPECIFICATIONS

Several alternative models of air travel demand have been considered in the development of this model: the Air Transport Energy Use Model (ATEM), developed by Oak Ridge National Laboratories (ORNL); the Transportation Energy and Emissions Modeling System (TEEMS), developed by Argonne National Laboratory (ANL); the Data Resources Incorporated (DRI) economic model; and forecasts produced by the Federal Aviation Administration (FAA). Each model contributed to the understanding of the dynamics of passenger travel and the assumptions underlying the forecast.

The emphasis of the ATEM model is on estimates of commercial passenger and freight aircraft stocks, and most closely corresponds to the AEO predecessor model.[23] RPM and RTM are estimated by separate models, both of which are functions of GNP and the cost of flying,

[23] Greene, D.L., et. al., *Air Transport Energy Use Model*, Center for Transportation Analysis, Oak Ridge National Laboratory, 4/91, Draft.

represented by the yield.[24] The yield is considered solely as a function of fuel price, whose contribution to total costs remains a fixed percentage. ATEM employs a modified constant elasticity specification as follows:

$$RPM_t = RPM_0 \cdot Pop \cdot GNPPC^{\beta_1(t)} \cdot Yield^{\beta_2(t)}$$

and:

$$RTM_t = RTM_0 \cdot GNP^{\beta_1(t)} \cdot Yield^{\beta_2(t)}$$

where RPM_0 and RTM_0 represent base year values, and the remaining variables are all indexed to their respective base year values. The elasticities, β_1 and β_2, are specified by the user for each decade of the forecast. This approach was not considered suitable for inclusion in NEMS due to the limited variable inputs, thereby decreasing sensitivity to economic and demographic conditions, and the reliance on user specification of elasticities.

TEEMS directly estimates domestic RPM and energy demand using a linear formulation. RPM values are considered to be functions of disposable personal income (DPI) and changes in jet fuel price (JP), while energy use is subsequently determined using exogenous projections of aircraft efficiency.[25] The travel demand equation is as follows:

$$RPM = .212(DPI) - .12(JP) - 262.344$$

where the coefficients have been estimated using a regression on 1970-1988 data. In determining consequent fuel consumption, TEEMS assumes an annual aircraft efficiency improvement of 1.5 percent over the next twenty years. This factor is the result of TEEMS' exogenous assessment of expected technology improvements as well as the mandated retirement of older aircraft to comply with noise regulations. Air cargo is projected as part of a separate freight demand model, within which a share of air ton-miles is allocated to dedicated cargo aircraft. Again, the limited reliance on variable inputs precludes the direct incorporation of this model in NEMS.

In the DRI model, air travel demand is influenced by the yield, or revenue per passenger-mile,

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[24] "Yield" is a commonly used term in the airline industry, and refers to the revenue per passenger-mile. It is used in most analyses as a normalized representation of ticket price.

[25] Argonne National Laboratory, *Forecast of Transportation Energy Demand Through the Year 2010*, ANL/ESD-9, 4/91.

whose algorithm is the same for both passengers and cargo:[26]

$$\text{Yield} = \text{Yield}_{T-1}\left[.65\left(\frac{\text{Fuel Cost}_T}{\text{Fuel Cost}_{T-1}}\right) + .35\left(\frac{\text{GNP}_T}{\text{GNP}_{T-1}}\right)\right]$$

Revenue passenger and cargo ton miles are subsequently calculated:

$$\text{RPM} = \text{Exp}^{5.78} \cdot \text{Yield}^{-.372} \cdot \left(\frac{\text{DPI}}{\text{Pop}}\right)^{3.33}$$

and:

$$\text{RTM} = \text{Exp}^{-.38} \cdot \text{Yield}^{-.12} \cdot \text{GNP}^{1.23}$$

Revenue passenger miles are then converted into pound-miles, using an average weight for passengers and baggage, and the demand for kerosene-type jet fuel is finally estimated as follows:

$$\text{Fuel Demand} = \text{Exp}^{-3.13} \cdot \text{RTM}_p^{.37} \cdot \text{RTM}_c^{.31} \cdot (\text{Real Fuel Price})^{-.14}$$

where the subscripts *p* and *c* refer to passengers and cargo, respectively. While the above models of RTM and RPM have more variable inputs than those models described previously, there seems to be no compelling reason to retain the constant elasticity specification in the development of the Air Travel Demand Model.

The primary function of the Federal Aviation Administration model is to forecast "workload measures", such as instrument operations at towered airports.[27] Such forecasts are used to estimate appropriate staffing levels, and new capital expenditures. The approach is a mixture of econometrics and intuition, using forecasts of secondary measures such as RPM, load-factors, and yields as process inputs.

Total operating cost and aircraft efficiency measures are first used to predict yields; these are then combined with GNP estimates to forecast total RPM and, subsequently, enplanements. Future airport operations are then estimated using predictions about load factors,[28] aircraft size, and trip length. Many of the key variables used in the estimation are the result of intuitive judgements

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[26] Model description obtained through personal communication with Mary Novak of DRI.

[27] Mayer, C.J., 1989. "Federal Aviation Administration Methodology," pp.9-29, in *Aviation Forecasting Methodology*, Transportation Research Circular Number 348, Transportation Research Board, National Research Council, Washington, D.C.

[28] The "load factor" is the ratio of revenue passenger-miles to available seat-miles; it provides an estimate of the average occupancy rate of passenger aircraft.

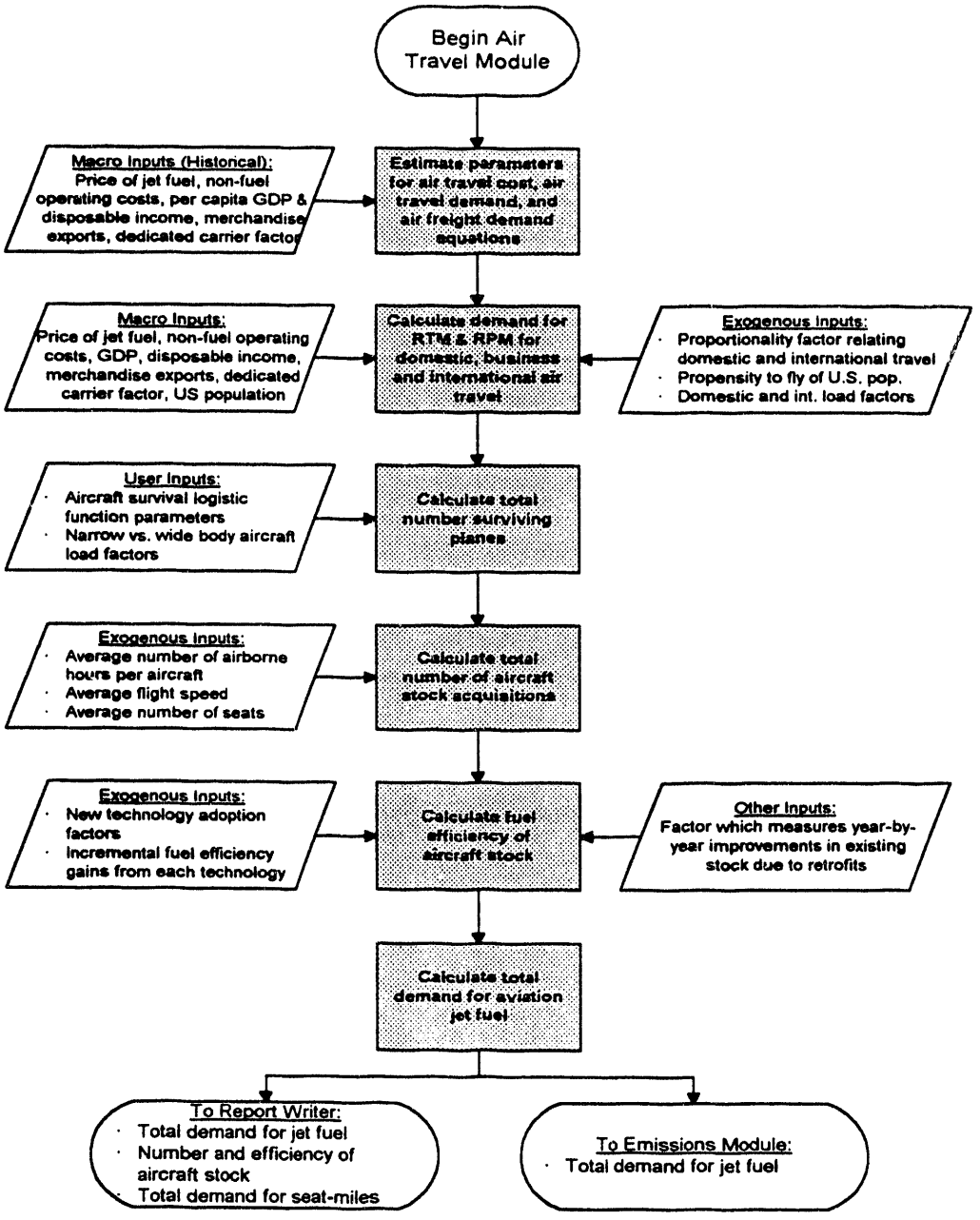
of aircraft manufacturers and airlines.

In considering the effect of deregulation on forecasting efforts, it is noted that the demand equation used to forecast RPM produces significantly different coefficients for pre- and post-deregulation data. Estimated price and income elasticities are significantly larger (in absolute value) in the post-deregulation era, reflecting structural changes in the airline industry. For example, the growth of the hub-and-spoke system has substantially increased the availability and convenience of air travel to many areas not previously served by major airlines. It is this dichotomy which has motivated the decision to restrict parameter estimation to the post-deregulation period.

MODEL STRUCTURE

The Air Travel Demand Model, as implemented in NEMS, is a series of linear equations estimated over the period 1979-1990. As noted above, it is assumed that domestic business and personal travel are motivated by different economic measures, and that personal travel is further affected by the demographic makeup of the United States. Key model relationships are presented below, in order of their appearance. Where numbers appear in place of variable names, parameters have been estimated statistically from historical trends. Descriptive statistics for all estimated parameters are provided in Appendix E, Tables E-4 through E-8. Also presented below in Figure 3D-1 is the flowchart for the Air Travel Module. At the end of this section are additional flowcharts which depict the calculations in the Air Travel Demand and Aircraft Fleet Efficiency models in more detail.

Figure 3D-1. Air Travel Module



1) Calculate the cost of flying:

$$YIELD = 4.22 + .94\,PJF + 65.42\,OPCST \tag{103}$$

where:

YIELD = Cost of air travel, expressed in cents per RPM
PJF = Price of jet fuel, in dollars per million Btu
OPCST = Non-fuel operating costs, in dollars per available seat-mile

2) Calculate the revenue passenger-miles per capita for each type of travel.

Business:

$$RPMBPC = -587.8 + .118\,\frac{TMC_GDP}{TMC_POPAFO} - 20.56\,YIELD \tag{104}$$

Personal:

$$RPMPPC = -126.8 + .050\,\frac{TMC_YD}{TMC_POPAFO} - 12.80\,YIELD \tag{105}$$

International:

$$RPMIPC = PCTINT \cdot (RPMBPC + RPMPPC) \tag{106}$$

where:

TMC_GDP = Gross domestic product, in 1987 dollars.
TMC_YD = Per capita disposable personal income, in 1987 dollars.
TMC_POPAFO = U.S. population
PCTINT = Proportionality factor relating international to domestic travel levels[29]

3) Calculate the revenue ton-miles (RTM) of air freight:

$$RTM = (-18{,}165.6 + 22.35\,TMC_EXDN87 + 5.77\,TMC_GDP) \cdot DFRT \tag{107}$$

where:

TMC_EXDN87 = Value of merchandise exports, in 1987 dollars
DFRT = Fraction of freight ton-miles transported by dedicated carriers[30]

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[29] This factor is an extrapolation of historic trends, and is tabulated in Appendix A, Table A-4.

[30] DFRT is obtained from an asymptotic extrapolation of past trends, and is tabulated in Appendix A, Table A-4.

4) Calculate total revenue passenger-miles flown for each category of travel, subsequently combining business and personal travel into a final domestic travel category:

$$RPMB = RPMBPC \cdot TMC_POPAFO \tag{111}$$

$$RPMP = RPMPPC \cdot TMC_POPAFO \cdot DI \tag{108}$$

$$RPMI = RPMIPC \cdot TMC_POPAFO \tag{109}$$

$$RPMD = RPMB + RPMP \tag{110}$$

where:

RPMB = Revenue passenger miles for business travel
RPMP = Revenue passenger miles for personal travel
RPMI = Revenue passenger miles for international travel
RPMD = Revenue passenger miles for all domestic travel
TMC_POPAFO = Total U.S. population
DI = Demographic index, reflecting the public's propensity to fly[31]

5) Calculate the total demand for available seat-miles, incorporating the estimated load factors of domestic and international travel, and converting ton-miles of freight into an equivalent seat-mile demand:

$$ASMDEMD = \left(\frac{RPMD}{LFDOM}\right) + \left(\frac{RPMI}{LFINTER}\right) + (RTM \cdot EQSM) \tag{112}$$

where:

ASMDEMD = Total demand for available seat-miles
LFDOM = Load factor for domestic travel
LFINTER = Load factor for international travel
EQSM = Equivalent seat-miles conversion factor; used to transform freight RTM's

[31] The Demographic Index is derived in Appendix F, Attachment 5.

3D-2. Aircraft Fleet Efficiency Model

RATIONALE

The Aircraft Fleet Efficiency Model of NEMS (AFEM) is a structured accounting mechanism which, subject to user-specified parameters, provides estimates of the number of narrow and wide-body aircraft available to meet passenger and freight travel demand. This mechanism also permits the estimation of fleet efficiency using a weighted average of the characteristics of surviving aircraft and those acquired to meet demand. This document presents the methodologies employed in the estimation, and preliminary results based on a separate analysis of travel demand.

In the model currently used to produce the 1993 Annual Energy Outlook (AEO), stock efficiency increases at a constant rate, with no explicit dependence on those parameters which would most affect it. This equation is an adaptation of the "best available technology" scenario proposed by ORNL in its analysis of aircraft efficiency:[32]

$$GPM_t = .0230 \cdot (1 - .0137)^{(t - 1985)}$$

where GPM_t represents the gallons per available seat mile in a given year. Given a forecast horizon of 2030, the 1.37 percent annual rate of improvement assumed in the current model leads to an approximate halving of aircraft energy intensity. The above equation assumes a consistent and uniform replacement of older aircraft with newer, more efficient units. Since, in fact, very few aircraft that have actually been retired in the last decade, this assumption seems inappropriate for a comprehensive air transportation modeling system.

The intent of this component of the NEMS Transportation Model is to provide a more intuitive, quantitative approach for estimating aircraft fleet energy efficiency. To this end, the model estimates surviving aircraft stocks and average characteristics at a level of disaggregation which is supportable by available data, and projects the fuel efficiencies of new acquisitions under different sets of economic and technological scenarios. The resulting fleet average efficiencies are returned to the Air Travel Demand Module of TERF to support the forecast of commercial passenger and freight carriers' jet fuel consumption to the year 2030.

Although the air model estimates fuel use from all types of aircraft, only commercial aircraft

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[32] *Energy Efficiency Improvement Potential of Commercial Aircraft to 2010*, David Greene, Energy Division, Oak Ridge National Laboratory, Draft Report, October, 1989.

efficiencies are explicitly modeled. Efficiencies of general aviation aircraft and military planes are not addressed. General aviation fuel use is directly estimated; jet fuel consumption is considered to be a fixed percentage of commercial aircraft demand, and aviation gasoline demand is projected using a time-dependent extrapolation. Military jet fuel use—both naphtha and kerosene based fuel—is estimated in another Module using forecasts of military budget trends.

ALTERNATIVE SPECIFICATIONS

In developing this methodology, two alternative approaches to the estimation of aircraft stocks and fleet efficiency have been considered: Oak Ridge National Laboratory's Air Transport Energy Use Model (ATEM), and an air transportation sub-module, being developed by Energy and Environmental Analysis, Inc. (EEA) for use by DOE's Office of Policy, Planning and Analysis in the Integrated Dynamic Energy Analysis Simulation model (IDEAS). While both employ the conventional methodology of matching new capacity acquisition with expected travel demand, each takes a different approach to the trade-off of flexibility and simplicity. The approach proposed in this component will incorporate aspects of each.

ATEM is a comprehensive effort to describe aircraft stock and efficiency changes.[33] This is a detailed stock vintaging model in which all aircraft are grouped into classes according to their market segment and size. The result is six classes, each described by their trip length and maximum passenger capacity. Passenger travel demand is distributed among the classes, approximating the previous year's distribution, and surviving aircraft capacity is subsequently determined, following the retirement of stock which has reached a uniform, user-specified retirement age. If aircraft supply exceeds travel demand in any class, excess capacity is permanently retired.

Excess travel demand in any class is met by the purchase of specific aircraft models with known operating characteristics and configurations, or generic models incorporating the most efficient new technologies available in a given year. As a default, all active aircraft models in a class would receive an equal market share of new purchases.[34] Using this model, the number of aircraft of every model is always known, as are their operating characteristics, configurations, and utilization rates. This is a very detailed and flexible model which can incorporate a wide variety of assumptions about future trends, but is therefore somewhat unwieldy, requiring an amount of

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[33] Rathi, A., Peterson, B., and Greene, D., *Air Transport Energy Use Model*, Oak Ridge National Laboratory, April 1991, Draft.

[34] *Ibid.*, pp. 2-9 — 2-14.

computer time which is inappropriate for use within NEMS.

Efficiency improvements are assumed to come from retrofitting existing aircraft with new technologies, the choice of which is partially dependent on fuel prices, and the incorporation of increasingly efficient technologies in newly acquired aircraft.[35] ATEM links the operating efficiency of existing aircraft to fuel prices, using an elasticity of -0.04, and a constant efficiency improvement of .03 percent per year.

In contrast, the commercial airline sector of the IDEAS model avoids this level of detail in favor of a simple aircraft vintaging model.[36] This model uses four age classes (0-10 years, 11-20 years, 21-30 years, and > 30 years), making no distinction between aircraft sizes or flight characteristics. This model assumes that average utilization rates and fuel efficiencies vary by aircraft age, and uses these characteristics to estimate the average fuel consumption per passenger mile of the fleet. The advantage of this approach is its ability to provide a quick overall estimate of trends, but its lack of policy levers, such as the effect of increased airport congestion or higher fuel prices, limits its usefulness in exploring the impact of various scenarios. The approach proposed in this report will represent a middle ground between these models—reducing the computation needs of ATEM without entirely sacrificing the ability to respond to economic, technological, or policy issues.

MODEL STRUCTURE

Total fleet efficiency is based on separate estimates of the stock and efficiency of the two types of aircraft considered by the model—narrow body and wide body.[37] The development of the hub and spoke system has made airlines inclined to invest in smaller aircraft in recent years, but increasing airport congestion provides the impetus for investments in larger craft. In 1990, narrow body aircraft accounted for approximately 56 percent of total available seat-miles, and wide body aircraft accounted for the remaining 44 percent. In this model, while the base case maintains the status quo, the share of total passengers and freight conveyed by each of these aircraft types may be altered by the user.

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[35] Greene, D.L., *Energy Efficiency Improvement Potential of Commercial Aircraft to 2010*, Oak Ridge National Laboratory, ORNL-6622, June 1990.

[36] Personal communication with Mike Sloane, Energy and Environmental Analysis, Inc.

[37] Narrow body aircraft, such as the Boeing 727, have seating for approximately 120-150 passengers, and are characterized by two banks of seats separated by a center aisle. Wide body aircraft, such as the Boeing 747, carry from 200-500 passengers in three banks of seats

The model operates in two stages: the first is an estimation of the total fleet of each type of aircraft required to meet projected demand in any given year; the second is a determination of stock efficiency given assumptions about the retirement rate of aircraft and the incorporation of energy-efficient technologies in new acquisitions.

Stock Estimation

This component first determines the demand for new commercial aircraft, based on the growth of travel demand and the retirement of older planes. Travel demand, expressed as a demand for equivalent seat-miles, is obtained from the Air Travel Demand Model, and is subsequently allocated between the two aircraft types considered by this model. The first step is to determine the fraction of seat miles attributable to each aircraft type. This is calculated using the fraction of total available seat miles provided by each type of aircraft in the previous year, adjusted by a constant which represents the effects of airport congestion:

$$\begin{aligned} SMFRAC_{NARROW,T} &= \left[\left(\frac{SMDEMD_{NARROW,T-1}}{SMDEMD_{T-1}}\right) + \delta \cdot \left(\frac{SMDEMD_{WIDE,T-1}}{SMDEMD_{T-1}}\right)\right] \; ; \; \delta \geq 0 \\ &= \left[\left(\frac{SMDEMD_{NARROW,T-1}}{SMDEMD_{T-1}}\right) \cdot (1-\delta)\right] \; ; \; \delta < 0 \qquad (114) \\ &\text{and} \\ SMFRAC_{WIDE,T} &= 1 - SMFRAC_{NARROW,T} \end{aligned}$$

where:

SMFRAC = Seat mile fraction, by type.
SMDEMD = Total seat-mile demand, by type, in year T.

This specification represents the shifting of a fraction of passenger load from one aircraft type to another, at a rate, δ, which is zero in the base case, but may be exogenously set. It is believed that the most probable value for this factor is negative—increasing the wide body market share—due, in addition to airport congestion, to the growth in the long-haul market, coupled with the longer range and lower seat-mile cost of wide body aircraft.[38]

The next step is to allocate the current year seat-miles demanded (calculated in the Air Travel Demand Model) among aircraft types:

[38] Personal communication with David Sepanen, Boeing Commercial Airplane Group, 9/23/92.

$$SMDEMD_{TYPE,T} = SMFRAC_{TYPE,T} \cdot SMDEMD_T \quad (113)$$

The number of surviving aircraft of each type are subsequently estimated. This model differs from other stock models in that retirements are not assumed to take place abruptly once the aircraft have reached a specified age. Instead, a logistic survival function estimates the fraction of originally delivered aircraft which survive after a given number of years. The sum across years gives an estimate of surviving stocks of each type of plane:

$$NSURV_{TYPE,T} = \sum_{VINT=0}^{n} NPCHSE_{TYPE,T-VINT} \cdot f(VINT) \quad (114)$$

where:

NSURV = Number of surviving planes in year T

NPCHSE = Number of planes originally purchased in the corresponding vintage year

VINT = The vintage, or number of years the aircraft have been in service

The logistic function, f(VINT), is defined as follows:

$$f(VINT) = \left[\frac{1}{1 + Exp^{-k(t_{.5} - VINT)}} \right] \quad (115)$$

where $t_{.5}$ represents the vintage at which half of the original stock is assumed to retire, and the constant, k, is explicitly determined by another assumption: the vintage at which ninety percent of the stock is retired:

$$k = \left[\frac{Ln(9)}{(t_{.9} - t_{.5})} \right] \quad (116)$$

Having established the number of surviving aircraft by type, the available aircraft capacity is calculated. Total available seat miles are estimated using average aircraft characteristics: utilization rates, cruising speed, and seats per aircraft. Surviving aircraft capacity (SMSURV) is calculated as follows:

$$SMSURV_{TYPE,T} = NSURV_{TYPE,T} \cdot ASMP_{TYPE,T}$$

$$\text{Where} \quad (117)$$

$$ASMP_{TYPE,T} = AIRHRS_{TYPE,T} \cdot AVSPD_{TYPE,T} \cdot SEATS_{TYPE,T}$$

where:

SMSURV = Surviving aircraft capacity

NSURV = The number of surviving aircraft, by type
ASMP = The available seat-miles per plane, by type
AIRHRS = The average number of airborne hours per aircraft
AVSPD = The average flight speed
SEATS = The average number of seats per aircraft

These average aircraft characteristics will be either set to default values, or will follow an assumed trend. Tables of these values are provided in Appendix A, Table A-4.

Surviving aircraft capacity is then compared with the travel demand estimates described above. The difference represents the additional capacity required to meet demand. Determining the number of aircraft of each type to add to the fleet is a matter of reorganizing the above equation:

$$NPCHSE_{TYPE,T} = \left[\frac{SMDEMD_{TYPE,T} - SMSURV_{TYPE,T}}{ASMP_{TYPE,T}}\right] \quad (118)$$

where:

NPCHSE = New purchases of aircraft to meet excess demand for travel

The resulting number of new aircraft is then added to surviving stock, and the data table is updated to reflect the newest vintage. This approach presumes that new aircraft are immediately available to meet demand. Actually, airlines' orders for planes are put in several years in advance of need based on estimates of air travel.

Fleet Efficiency

Average fleet efficiency is estimated using a series of simplifying assumptions. First, the new stock efficiency is determined for each type of aircraft, using the following approach:

$$SMPG_{TYPE,T} = \left[\left(\frac{STKFRAC_{OLD,TYPE,T}}{(1 + \rho_{TYPE}) \cdot (SMPG_{OLD,TYPE,T})}\right) + \left(\frac{STKFRAC_{NEW,TYPE,T}}{SMPG_{NEW,TYPE,T}}\right)\right]^{-1} \quad (119)$$

where:

SMPG = Aircraft fuel efficiency in seat-miles per gallon
$STKFRAC_{OLD}$ = Fraction of seat-miles handled by existing stock
$STKFRAC_{NEW}$ = Fraction of seat-miles handled by newly acquired stock
ρ = Rate at which fuel efficiency of existing aircraft increases annually due to retrofitting

For simplicity, it is assumed that load factors do not vary with the age of the plane; these shares are therefore assumed to be solely dependent on the respective number of planes, as follows:

$$STKFRAC_{OLD,TYPE,T} = \frac{NSURV_{TYPE,T}}{(NSURV_{TYPE,T} - NPCHSE_{TYPE,T})}$$

and

$$STKFRAC_{NEW,TYPE,T} = (1 - STKFRAC_{OLD,TYPE,T}) \quad (120)$$

The factor multiplying the $SMPG_{OLD}$ reflects the user's assumption that stock efficiency for each type of aircraft increases at a uniform annual rate of ρ due to the retrofit of older aircraft with new technology, and the retirement of obsolete planes In the absence of user specification, the model will use default values of 0.44 percent and 0.18 percent for narrow and wide body aircraft, respectively. These figures are based on the average annual improvements in efficiency for each type of aircraft between 1980 and 1990.

Efficiency improvements of newly acquired aircraft are determined by technology choice which is, in turn, dependent on the year in question, the type of aircraft and the price of fuel. Appendix A, Table A-5, tabulates the technology choices and the expected efficiency improvements of aircraft incorporating those technologies. The model also sets a lower limit for efficiency gains by new aircraft, based on the assumption that new planes will be at least five percent more efficient than the stock efficiency of surviving aircraft. This provision is triggered if the incorporation of new technologies fail to sufficiently increase the efficiencies of new acquisitions.

In order to model a smooth transition from old to new technologies, the efficiencies of new aircraft acquisitions are based on several logistic functions which reflect the commercial viability of each technology. For each technology, a Technology Penetration Function is defined as follows:

$$Penetration_{TECH} = \frac{1}{1 + \exp^{-(PE+TE-6)}} \quad (121)$$

where:

Penetration = The fraction of new aircraft incorporating a given technology
PE = The influence of fuel prices on technology penetration
TE = The influence of time on technology penetration

The two arguments, the price effect (*PE*) and the time effect (*TE*), are based on the assumption that the rate of technology incorporation is determined not only by the magnitude of a given technology's price advantage, but also by the length of time in which the technology has been commercially viable. *TE*, the time effect, is defined as a user-specified constant multiplied by the number of years following the trigger year in which the trigger price has been met or

exceeded. This constant strongly influences the slope of the logistic curve and has been initially set to 0.7 to reflect historical trends in technology adoption. The larger this factor, the more abrupt the transition between zero and full implementation of the considered technology. The factor *-6* represents an *ad hoc* adjustment which anchors the logistic curve, thus ensuring that technologies are not incorporated prior to their commercial viability. The price effect, *PE*, is defined as follows:

$$\begin{gathered} PE = 10 \cdot \frac{[\text{Fuel Price} - \text{Trigger Price}]}{\text{Fuel Price}} \\ \text{when} \\ (0 < \text{Trigger Price} \leq \text{Fuel Price}) \\ \text{and} \\ PE = 0 \ , \quad \text{Otherwise} \end{gathered} \tag{122}$$

where 10 is a scaling factor.

Given the variety of non-exclusive technologies, some assumptions must be made: (1) technologies enter the mix as they become viable and cost competitive; (2) the inclusion of a technology with a higher trigger price is dependent on the prior use of those technologies with lower trigger prices; and (3) efficiency gains attributable to each technology are directly proportional to the level of penetration of that technology.

Following the estimation of stock efficiency by body type, overall fleet efficiency is estimated in a similar manner:

$$SMPG_T = \left[\sum_{TYPE=1}^{2} \left(\frac{SMFRAC_{TYPE,T}}{SMPG_{TYPE,T}} \right) \right]^{-1} \tag{123}$$

where, in this instance, the shares are not determined by the number of planes of each type, but by historical trends and expectations of total available seat miles offered by each type of aircraft. Changes in these trends are guided by assumptions concerning airport congestion, and the maturation of the hub and spoke system.

Estimating Fuel Consumption

Estimating the demand for jet fuel is simply a matter of combining the output of these two models:

$$JFDEMD_T = \frac{SMDEMD_T}{SMPG_T}$$

where:

JFDEMD = The total demand for aviation jet fuel

This result is subsequently augmented by a constant five percent to reflect the use of jet fuel in private planes.

Figure 3D-2. Air Travel Demand Model 1: Seat-Mile Demand Estimation

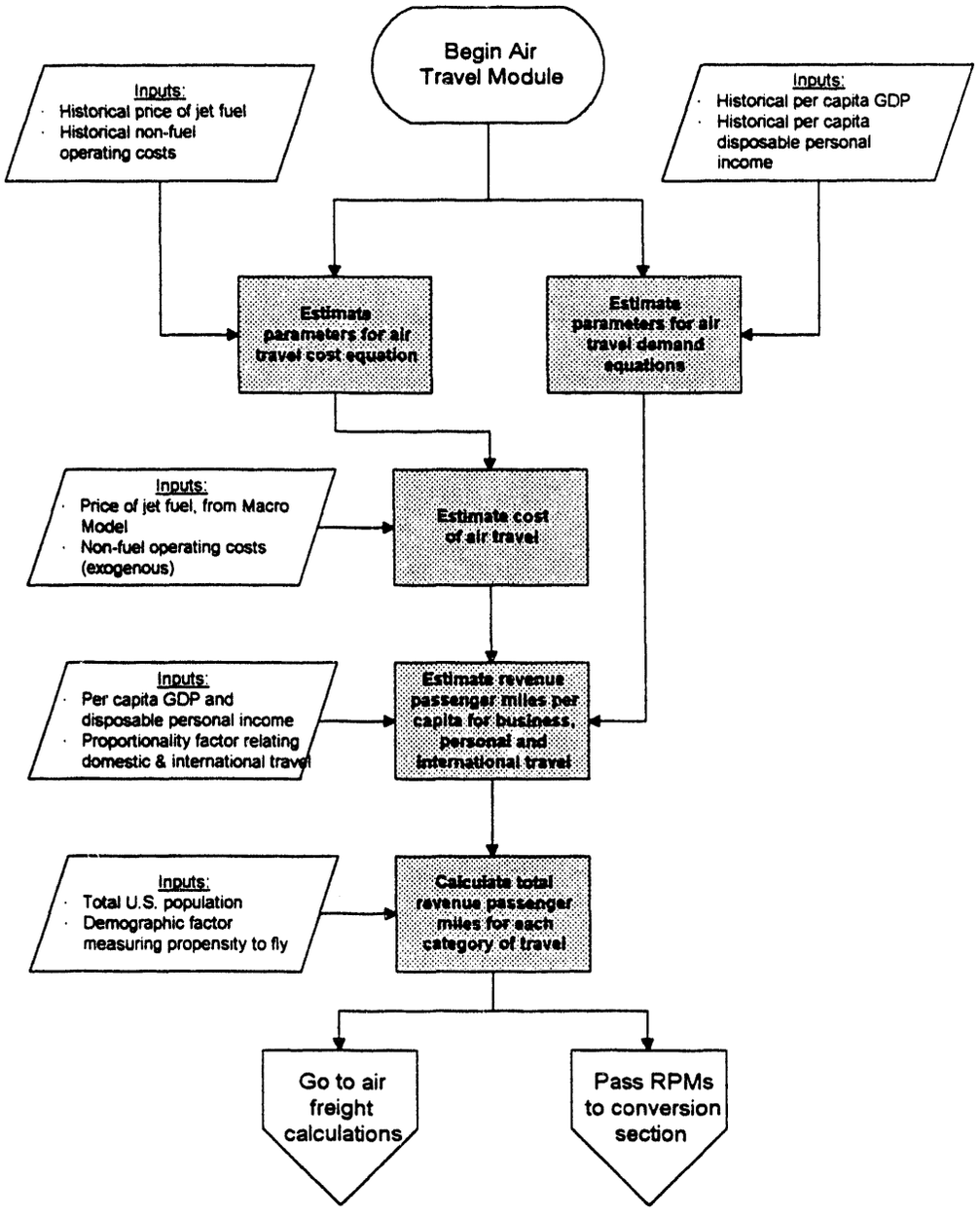


Figure 3D-3. Air Travel Demand Model 2: Air Freight Demand Estimation

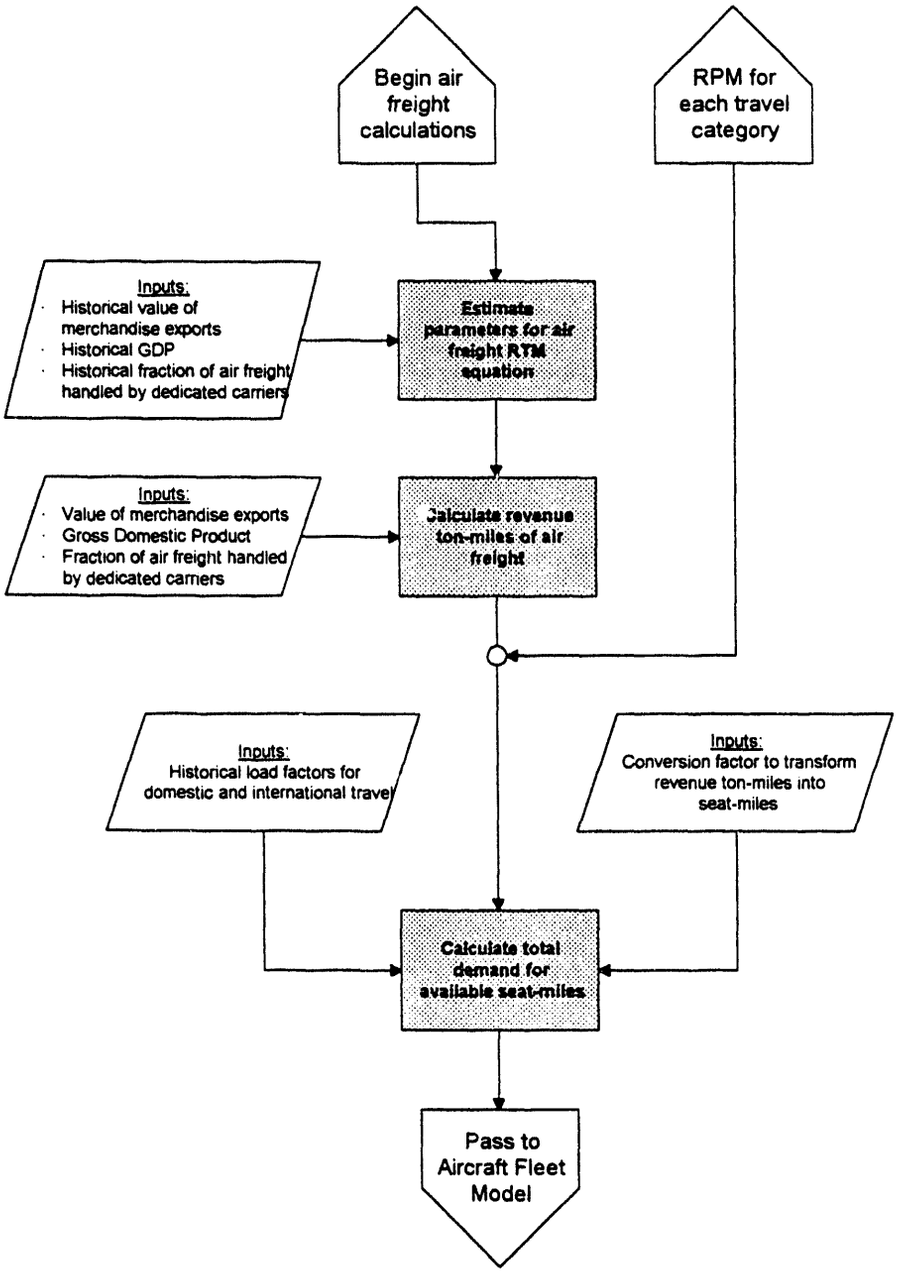


Figure 3D-4. Aircraft Fleet Efficiency Model 1: Process Changes to Existing Fleet

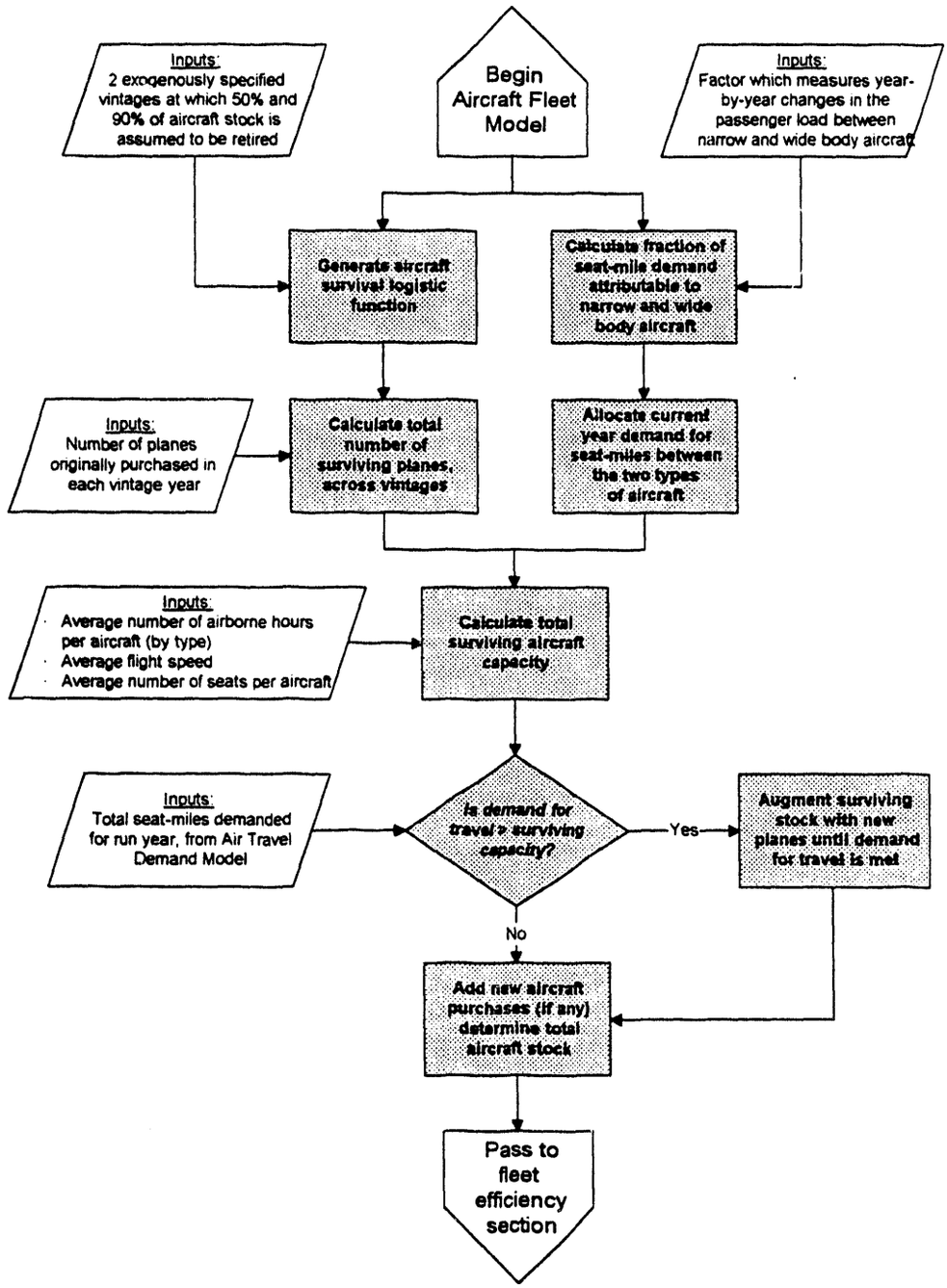
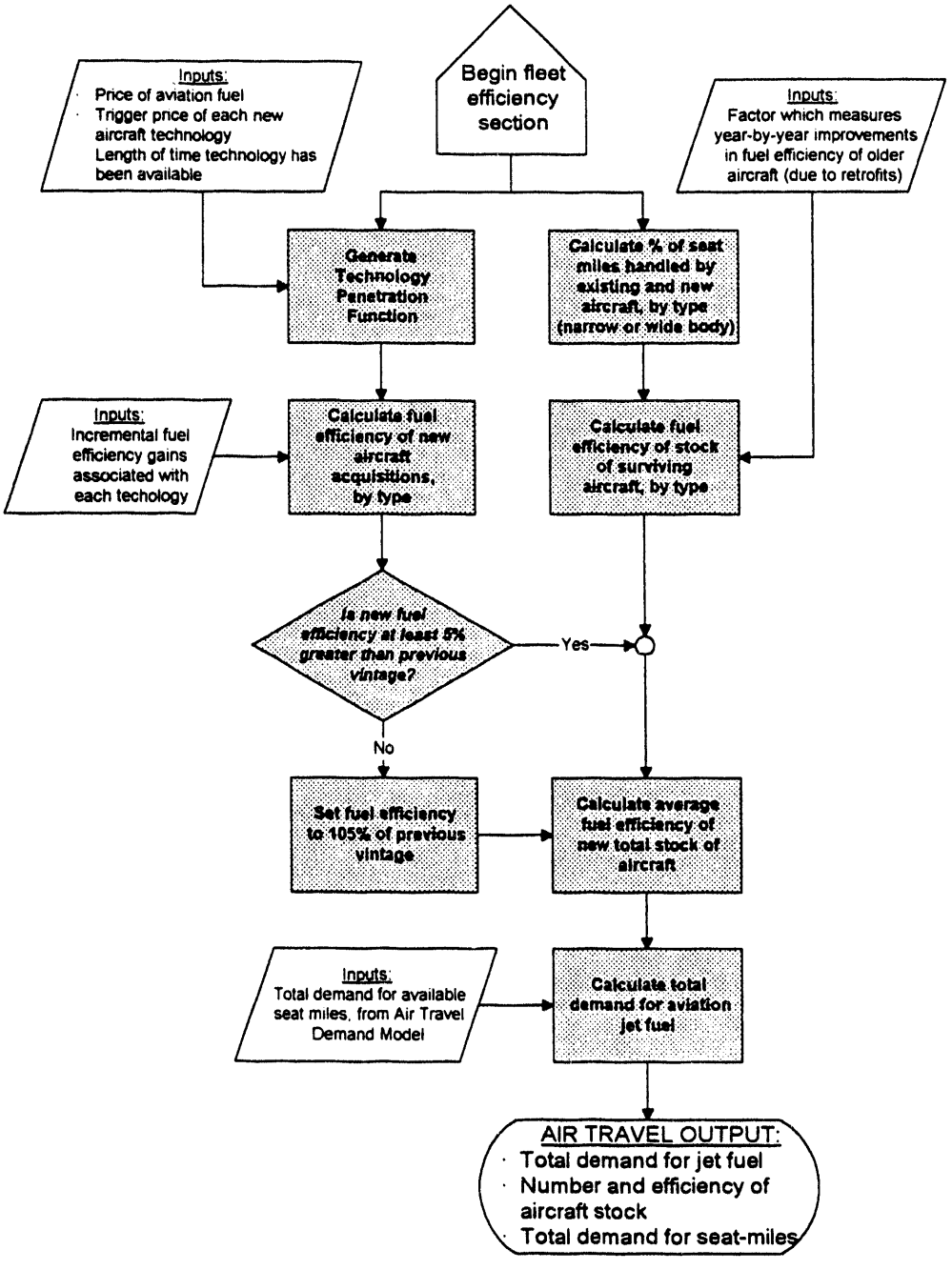


Figure 3D-5. Aircraft Fleet Efficiency Model 2: Process New Stock and Calculate Fuel Demand



3E. Freight Transport Module

RATIONALE

The freight component of the NEMS Transportation Model addresses the three primary modes of freight transport: truck, rail, and marine. This model uses NEMS forecasts of real fuel prices, trade indices, and forecasts of selected industries' output from the Macroeconomic Model to estimate travel demand for each freight mode, and the fuel required to meet that demand. The carriers in each of these modes are characterized, with the possible exception of trucks, by very long operational lifetimes, and the ability to extend these lifetimes through the retrofitting process. This results in a low turnover of capital stock and the consequent dampening of improvement in average energy efficiency. Given the long forecast horizon, however, this component will provide estimates of modal efficiency growth, driven by assumptions about systemic improvements and modulated by fuel price forecasts.

The freight model currently used for the AEO is an aggregate version of the Argonne National Laboratory freight model, FRATE. Forecasts are made for each of the four modes of freight transport: trucks, rail, ships, and air. In each case, travel forecasts are based on the industrial production of specific industries, travel growth in most cases being directly proportional to increases in value added. This is then converted to energy demand using the average energy intensity for the mode in question. Total energy demand is subsequently shared out to the various types of fuel used for freight transport, under the assumption that relative shares remain constant. As each mode is considered in the aggregate, no distinction is drawn between classes of carrier, such as trucks of different size.

The freight transport model developed for NEMS is an adaptation of the AEO model, providing flexibility for future developments, and incorporating another level of detail in the specification of modes. This is accomplished by stratifying the trucking sector according to size classes, and providing for similar stratification of the other modes, as needed. Parameters relating industrial output tonnage to changes in value added have been explicitly incorporated.

ALTERNATIVE SPECIFICATIONS

Argonne National Laboratory's Transportation Energy and Emissions Modeling System (TEEMS) provides the foundation for this component. This model links several disaggregate models to produce a forecast of transportation activity, energy use, and emissions. The freight sector module estimates future-year activity (ton-miles or vehicle-miles) and energy consumption by mode.

Indices of sectoral output are supplied by a macroeconomic model. A mode choice model then computes ton-miles traveled by truck, rail, water, and air for 24 commodity sectors based on commodity characteristics, changes in fuel price, energy intensities, and modal operating characteristics. An accounting submodel uses modal energy intensities, load factors, and size/subactivity allocation factors to compute activity and energy consumption by fuel type for each freight mode.[39]

The FRATE model is highly disaggregate, incorporating a variety of commodity and mode-dependent characteristics used by a shipper to maximize utility. Forecasts are dependent on base year (1985) freight movement data, which have been obtained from several sources. The 1985 *One Percent Rail Waybill Sample*[40] and the Association of American Railroads' *Railroad Facts*[41] were used to estimate rail ton-miles of travel; *Waterborne Commerce of the United States*,[42] published by the U.S. Army Corps of Engineers, was used to estimate marine ton-miles of travel; truck vehicle-miles and ton-miles of travel were estimated using the *Truck Inventory and Use Survey*,[43] and growth indices of sectoral economic output from Data Resource Inc.'s macroeconomic model.[44] Truck energy consumption is projected using fuel economy in terms of miles per gallon and average load factors. Rail and marine energy intensities are computed using the total fuel sales by mode as published in the *Petroleum Marketing Monthly*.[45] The differences between energy intensities of various sectors have been held constant from 1977.

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[39] This summary is derived from *Forecast of Transportation Energy Demand Through the Year 2010*, Energy Systems Division, Argonne National Laboratory, ANL/ESD-9, April, 1991, p. 34, et. seq.

[40] *One Percent Waybill Sample*, Federal Railroad Administration, Washington, D.C., 1987.

[41] *Railroad Facts*, Association of American Railroads, Washington, D.C., 1987.

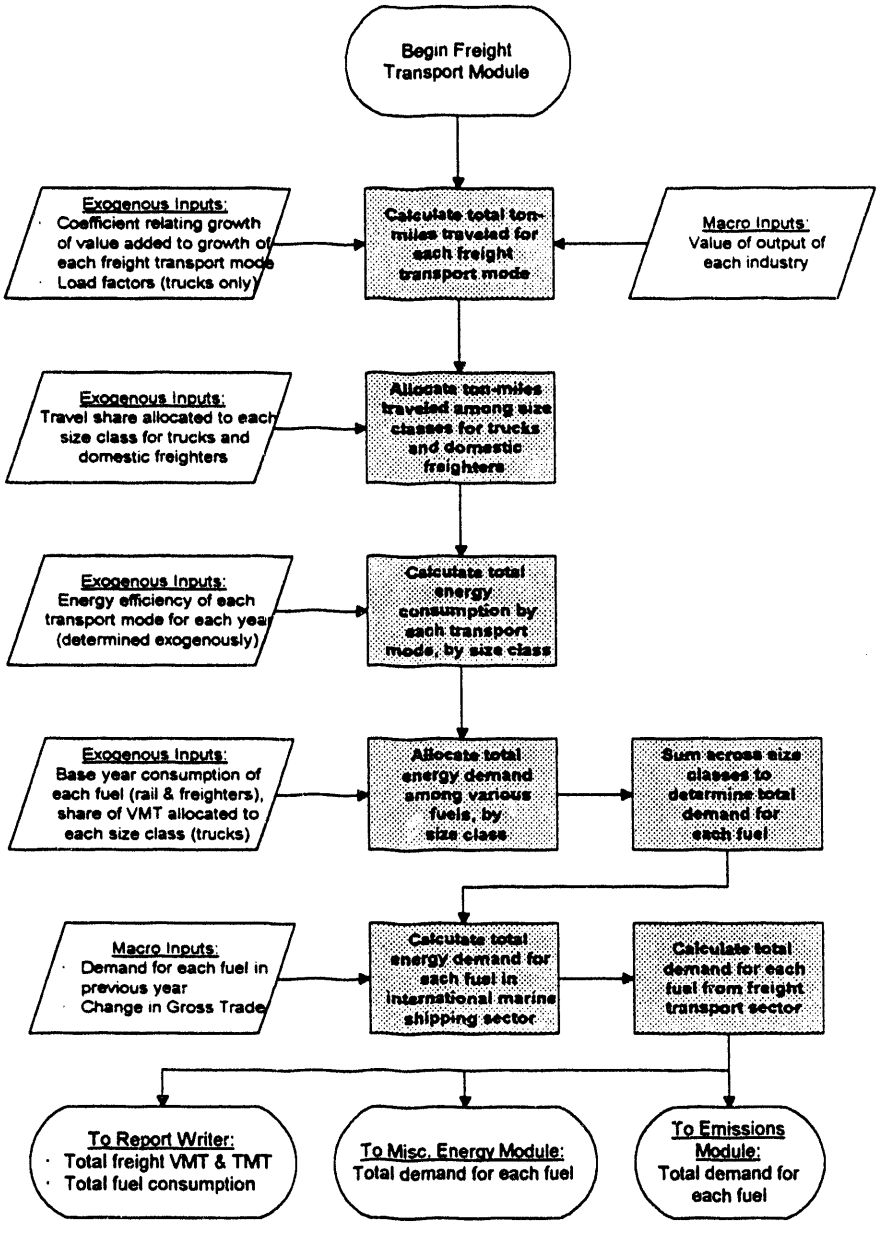
[42] *Waterborne Commerce of the United States*, U.S. Army Corps of Engineers, Water Resources Support Center, New Orleans, LA, 1987.

[43] *The 1982 Truck Inventory and Use Survey: Public Use Tape*, Bureau of the Census, U.S. Department of Commerce, Washington, D.C., 1984.

[44] *The DRI Annual Model of the U.S. Economy: PC Version*, Data Resources, Inc., Lexington, MA, 1986.

[45] *Petroleum Marketing Monthly*, Energy Information Administration, U.S. Department of Energy, Washington, D.C., 1986.

Figure 3E-1. Freight Transport Module



MODEL STRUCTURE

The NEMS Freight Transport Module retains the structure used in the predecessor AEO model, aggregating the value of output from various industries into a reduced classification scheme, and relating the demand for transport to the growth in the value of output of each industrial category. The relationships used for truck, rail, and waterborne freight are presented in sequence below. The flowchart for the Freight Transport Module is presented in Figure 3E-1 above. Additional flowcharts presenting Freight Module calculations in more detail can be found at the end of this section.

3E-1. Highway Freight Model

The growth in fuel demand by trucks is considered to be directly related to the growth in industrial output forecast for specific industries. The freight truck module will estimate the total ton-miles of highway freight, then allocate shares of that travel demand amongst the three classes of trucks considered in this component. For a given set of industries:

$$FTMT_{I,T} = FTMT_{I,T_0} \cdot FACTR_{I,Mode} \cdot \left[\frac{OUTPUT_{I,T}}{OUTPUT_{I,T_0}}\right] \quad (125)$$

where:

FTMT = Total highway freight traffic for industry *I* in year *T*
OUTPUT = Value of output of industry *I*, in base year dollars
FACTR = Freight adjustment coefficient for trucks
I = Index referring to NEMS industrial sector

The freight adjustment coefficients correct for the difference between the rate of growth of the value added and the freight requirements of the specified industry and mode of transport. This total freight travel demand is subsequently converted to VMT using the following relationship:

$$FVMT_{I,T} = \frac{FTMT_{I,T}}{FRLOAD_I} \quad (126)$$

where:

FVMT = Total freight vehicle-miles traveled for a given industry in year *T*
FRLOAD = Load factor associated with a given industry's output

The load factor ratios are expressed as the ratio of ton-miles traveled to vehicle-miles traveled, and are assumed to remain constant throughout the forecast. The total VMT attributed to freight

trucks is the sum over all industries:

$$FVMT_T = \sum_I FVMT_{I,T} \tag{127}$$

The total freight VMT is next allocated among the three classes of trucks considered by the model:

$$FVMTSC_{C,T} = TS_{C,T} \cdot FVMT_T \tag{128}$$

where:

FVMTSC = Total highway freight VMT, by size class
TS = Travel share allocated to trucks of class *C* in a given year
C = Index referring to truck size class

Until further research can provide an indication of how travel shares are changing over time, they will be considered constant, and allocated according to the most recent data:

$$TS_{C,T} = \frac{FVMT_{C,T_0}}{FVMT_{T_0}} \tag{129}$$

Total VMT associated with each class of truck is then allocated among the various fuel technologies (such as diesel or gasoline) considered by the model:

$$FVMTECHSC_{C,TECH,T} = FVMTSC_{C,T} \cdot FLVMTSHR_{C,TECH,T} \tag{130}$$

where:

FVMTECHSC = Total highway freight VMT, by size class and technology

where FLVMTSHR represents the share of each technology in total truck VMT, and is determined as follows:

$$FLVMTSHR_{C,TECH,T} = \left[\frac{FVMT_{C,TECH,T_0}}{FVMT_{C,T_0}}\right] \cdot GROWTH_{TECH} \tag{131}$$

In the above equation, each technology's VMT share changes over time, according to an exogenously specified $GROWTH_{TECH}$ factor. These shares are subsequently renormalized to 1.

The next step is to calculate freight truck fuel efficiency. Efficiency improvements within the various classes of trucks also have a significant impact on fuel demand. Improvements are considered to fall into two categories: time-sensitive and price-sensitive. It is assumed that the average efficiency of each class will improve at a steady rate, as determined by historical

patterns. This would be the result of simple retrofit measures used to increase aerodynamics, the retirement of older, less efficient stock, and the acquisition of newer, more efficient trucks. Increases in fuel prices are also expected to stimulate gains in efficiency, either by making technological improvements cost effective, or by encouraging the more efficient scheduling of freight shipments. These two forms of improvement are further assumed to be multiplicative:

$$FMPG_{C,TECH,T} = FMPG_{C,TECH,T-1} \cdot (1 + \beta 1_C) \cdot \left(MAX \left\{ 1.0, \left[\frac{TPMGTR_T}{TPMGTR_{T-1}} \right] \right\} \right)^{\beta 2_C} \quad (132)$$

where:

$FMPG_{C,TECH,T}$ = Freight truck fuel efficiency, by size class and technology
$TPMGTR_{C,T}$ = Price of motor gasoline for trucks, from Macro Module

The time sensitivity coefficient, $\beta 1_C$, is exogenously specified, and the fuel price sensitivity coefficient, $\beta 2_C$, is estimated from historical trends. One final assumption holds that efficiency changes motivated by fuel price occur only in the positive sense—that is, a reduction in the price of fuel will not result in a lowering of truck efficiency.

Fuel use is subsequently estimated, using the average fuel efficiency for each class of truck:

$$FFD_{C,TECH,T} = \frac{FVMTECHSC_{C,TECH,T}}{FMPG_{C,TECH,T}} \cdot QBTU_{TECH} \quad (133)$$

where:

$FFD_{C,TECH,T}$ = Fuel demand for a given class of truck and fuel type
$FMPG_{C,TECH,T}$ = Fuel efficiency for each truck class
$QBTU_{TECH}$ = Heat content of fuel used by each technology, in MMBtu per gallon

This is then allocated to the nine census regions and summed over size classes:

$$TQFREIR_{TECH,R,T} = \sum_{C=1}^{3} FFD_{C,TECH,T} \cdot SEDSHRDS_{C,TECH,T} \quad (134)$$

where:

$TQFREIR_{TECH,T}$ = Total regional fuel consumption for each technology
$SEDSHRDS_{C,TECH,T}$ = Regional share of truck fuel consumption, from SEDS

3E-2. Rail Freight Model

Rail forecasts represent a simplification of the freight trucking approach, in that only one class

of freight rail and vehicle technology is considered. Projections of energy use by rail are driven by forecasts of ton-miles travelled for each of the industrial categories used in the trucking sector. The algorithm is virtually identical to the one used for trucks:

$$RTMT_T = \sum_{I=1}^{10} RTMT_{I,T_0} \cdot FACR_I \cdot \left[\frac{OUTPUT_{I,T}}{OUTPUT_{I,T_0}}\right] \tag{135}$$

where:

RTMT = Total rail ton-miles traveled for industry *I* in year *T*
OUTPUT = Value of output of industry *I*, in base year dollars
FACR = Coefficient relating growth of value added with growth of rail transport

Energy consumption is then estimated using the projected rail energy efficiency:

$$TQRAILT_T = FERAIL_T \cdot RTMT_T \tag{136}$$

where:

TQRAILT = Total energy consumption by freight trains
FERAIL = Rail energy efficiency

where rail efficiency gains resulting from technological development and increased system efficiency are based on an exogenous analysis of trends.

This aggregate energy demand is used to estimate the demand for the various fuels used for rail transport, adjusting the previous year's demand for a given fuel by the fractional increase in overall energy requirements:

$$TQRAIL_{FUEL,T} = TQRAIL_{FUEL,T-1} \cdot \left(\frac{TQRAILT_T}{TQRAILT_{T-1}}\right) \tag{137}$$

where:

$TQRAIL_{FUEL,T}$ = Total demand for each fuel by rail freight sector in year *T*

This is based on the assumption that the relative shares of each fuel remains constant across the forecast horizon, and that there is little or no room for fuel substitution as prices vary.

Fuel consumption is then allocated to each region:

$$TQRAILR_{TECH,R,T} = TQRAIL_{C,TECH,T} \cdot SEDSHRDS_{C,TECH,T} \quad (138)$$

where:

$TQRAILR_{TECH,T}$ = Total regional fuel consumption for each technology
$SEDSHRDS_{TECH,T}$ = Regional share of rail freight fuel consumption, from SEDS

3E-3. Waterborne Freight Model

Two classes of waterborne transit are considered in this component: domestic marine traffic and freighters conducting foreign trade. This is justified on the grounds that vessels which comprise freighter traffic on rivers and in coastal regions have different characteristics than those which ply international waters.

Domestic Marine

Once again, the estimation of total domestic waterborne travel demand is driven by forecasts of industrial output:

$$STMT_T = \sum_{I=1}^{10} STMT_{I,T_0} \cdot FACS_I \cdot \left[\frac{OUTPUT_{I,T}}{OUTPUT_{I,T_0}}\right] \quad (139)$$

where:

STMT = Total ton-miles of waterborne freight for industry *I* in year *T*
OUTPUT = Value of output of industry *I*, in base year dollars
FACS = Coefficient relating growth of value added with growth of shipping transport

This total is subsequently shared out among classes of domestic freighter:

$$STMT_{C,T} = TS_{C,T} \cdot STMT_T \quad (140)$$

where:

TS = Travel share allocated to vessels in class *C*

Travel shares are considered constant, and allocated according to the most recent data:
At present, only one class of domestic waterborne transport is considered, but as further research is conducted, a greater level of detail may be justified.

$$TS_C = \frac{STMT_C}{STMT_{Total}} \quad (141)$$

Fuel use is subsequently estimated, using the average energy efficiency for each class of freighter (currently one class):

$$SFDT_T = FESHIP_T \cdot STMT_T \quad (142)$$

where:

SFDT = Domestic ship energy demand
FESHIP = Average fuel efficiency

Estimated changes in energy intensity will be developed exogenously. The next step is to allocate total energy consumption among three fuel types (distillate fuel, residual fuel oil and gasoline):

$$SFD_{IF,T} = SFDT_T \cdot SFSHARE_{IF,T} \quad (143)$$

where:

SFD = Domestic ship energy demand, by fuel
SFSHARE = Domestic shipping fuel allocation factor
IF = Index referring to shipping fuel type

The factor which allocates energy consumption among the three fuel types is based on 1990 AEO numbers and is held constant throughout the run period.

Total energy demand is then regionalized:

$$TQSHIPR_{IF,REG,T} = SFD_{IF,T} \cdot SEDSHR_{IF,REG,T} \quad (144)$$

where:

TQSHIPR = Total regional energy demand by domestic freighters
SEDSHR = Regional shares of fuel demand, from SEDS

Although only one class of vessel is considered at the present time, the model was designed to allow further stratification should more detailed data become available.

International Marine

Fuel demand in international marine shipping is directly estimated, linking the level of international trade with the lagged consumption of the fuel in question:

$$ISFDT_T = ISFDT_{T-1} + \left[\frac{GROSST_T}{GROSST_{T-1}} - 1 \right] \cdot 0.5 \cdot ISFDT_{T-1} \quad (145)$$

where:

ISFDT = Total international shipping energy demand in year *T*
GROSST = Value of Gross Trade (imports + exports), from Macro Model

Total energy demand is then allocated among the various fuels as above:

$$ISFD_{IF,T} = ISFDT_T \cdot ISFSHARE_{IF,T} \quad (146)$$

where:

ISFD = International freighter energy demand, by fuel
ISFSHARE = International shipping fuel allocation factor

Regional fuel consumption is then calculated:

$$TQISHIPR_{IF,IR,T} = ISFD_{IF,T} \cdot SEDSHR_{IF,IR,T} \quad (147)$$

where:

TQISHIPR = Total regional energy demand by international freighters
SEDSHR = Regional shares of fuel demand, from SEDS

Figure 3E-2. Highway Freight Model

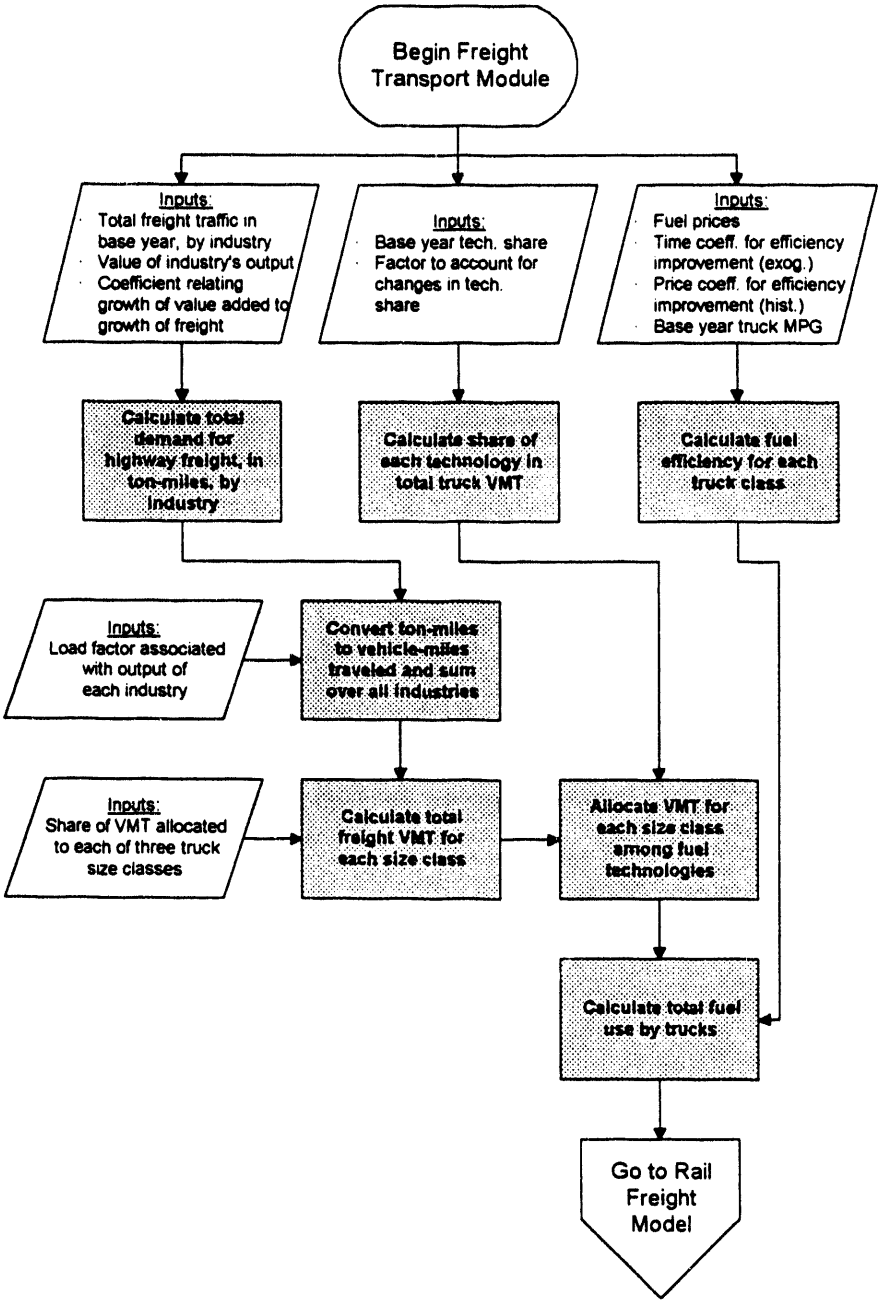


Figure 3E-3. Rail Freight Model

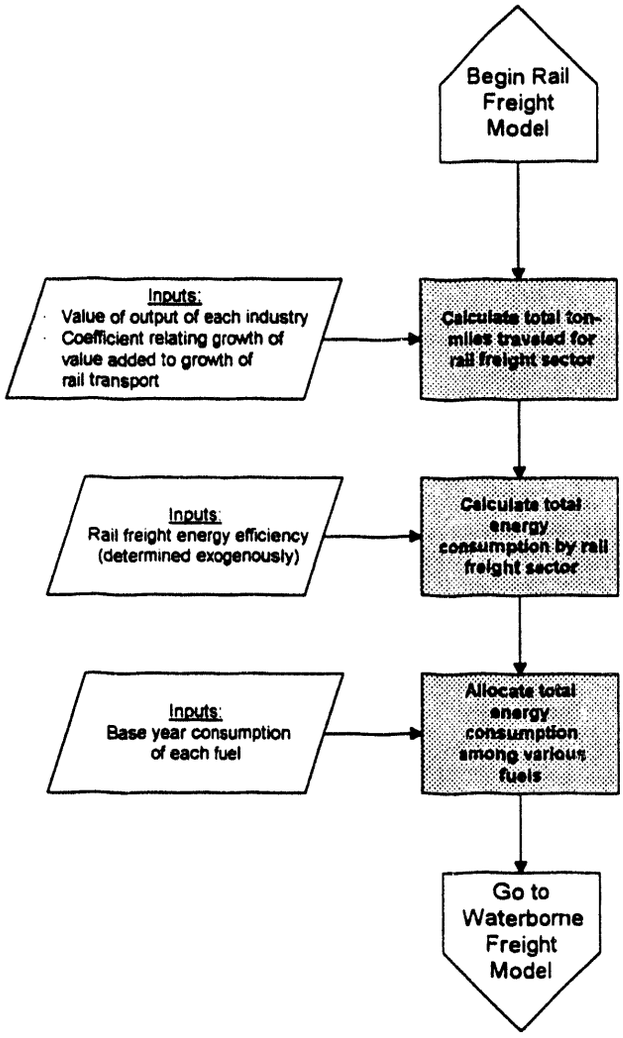
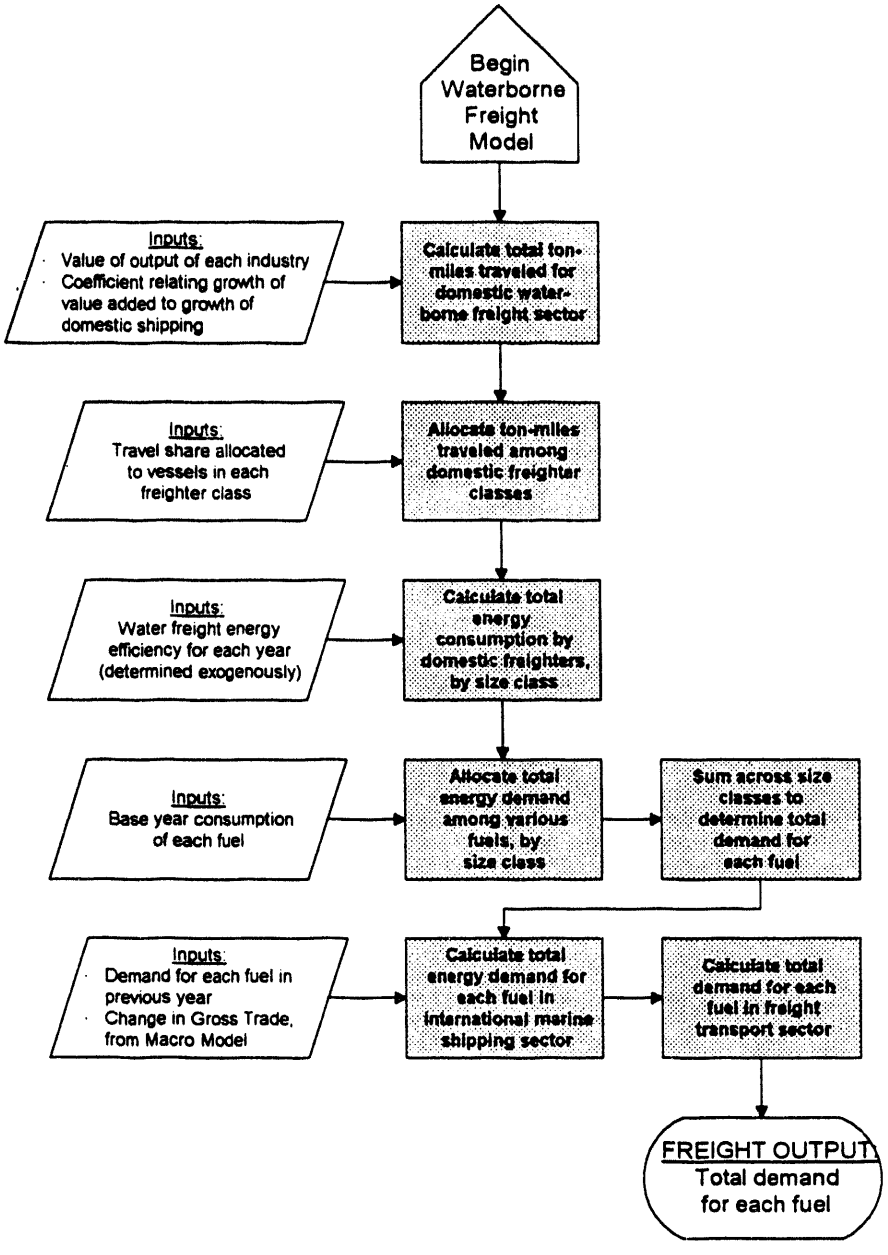


Figure 3E-4. Waterborne Freight Model



3F. Miscellaneous Energy Use Module

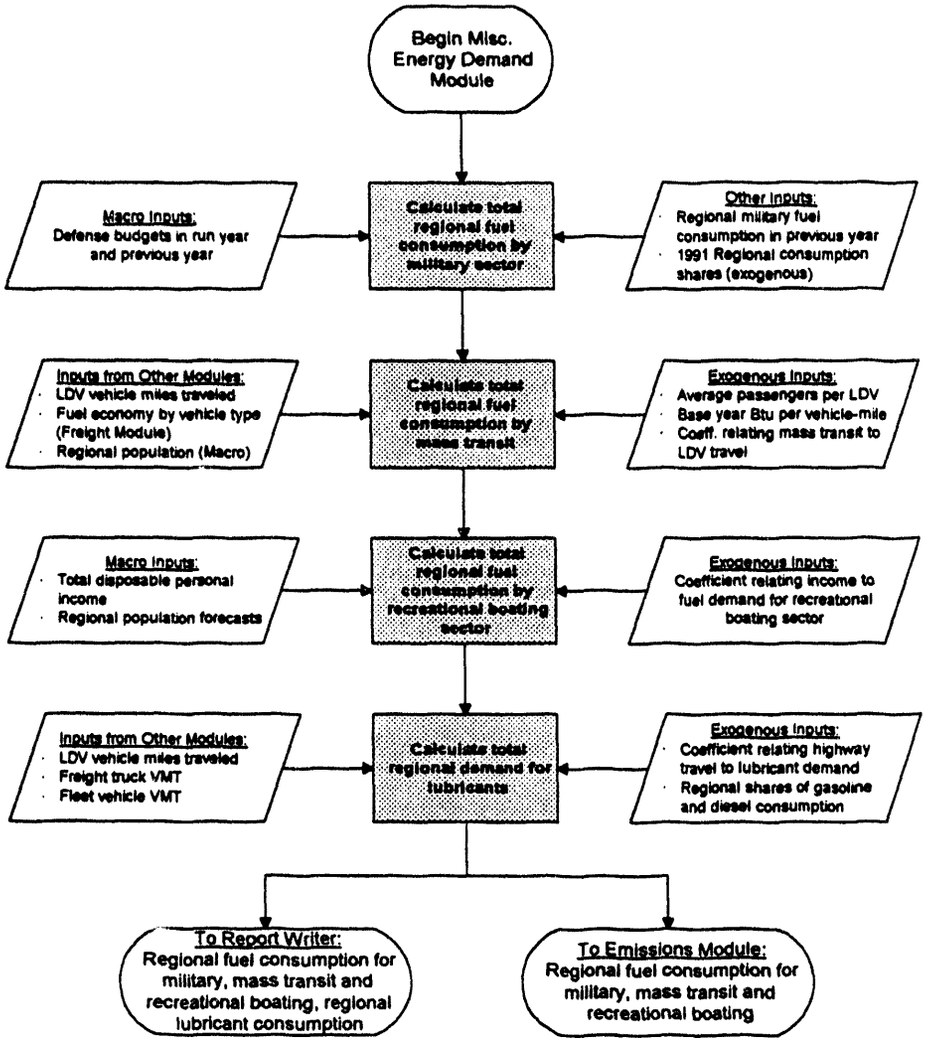
RATIONALE

This module addresses the projection of demand for several transportation fuels and end-use categories that have not been considered in earlier modules. These energy uses include military operations, mass transit (passenger rail and buses), recreational boating, and lubricants used in all modes of transportation. The NEMS approach represents an incremental improvement over the estimation methodology used in the predecessor AEO model.

In determining the impact of military operations, the predecessor model makes adjustments to energy consumption on a fuel-by-fuel bases to reflect recent military consumption levels. These levels are then assumed to remain constant over the forecast. In contrast, the NEMS model uses military budget estimates to forecast changes in fuel demand. In the public transit sector, the predecessor model does not explicitly consider passenger rail, which accounts for approximately fifteen percent of total rail energy consumption, or buses, which account for approximately one percent of total highway fuel consumption; energy use for each of these modes is considered as part of the benchmarking process, as is fuel use in recreational boats. NEMS models these sectors explicitly.

The flowchart for the Miscellaneous Energy Demand Module is presented below. Additional flowcharts portraying Miscellaneous Energy Demand Module calculations in more detail can be found at the end of this section.

Figure 3F-1. Miscellaneous Energy Demand Module



MODEL STRUCTURE

3F-1. Military Demand Model

Demand for fuel for military operations is considered to be proportional to the projected military budget. The fractional change in military budget is first calculated:

$$MILTARGR_T = \frac{TMC_GFML87_T}{TMC_GFML87_{T-1}} \quad (148)$$

where:

MILTARGR = The growth in the military budget from the previous year
TMC_GFML87 = Total defense budget in year T, from the macro economic segment of NEMS

Total consumption of each of four fuel types is then determined:

$$MFD_{IF,T} = MFD_{IF,T-1} * MILTARGR_T \quad (149)$$

where:

MFD = Total military consumption of the considered fuel in year T
IF = Index of fuel type: 1=Distillate, 2=Naphtha, 3=Residual, 4=Kerosene

Consumption is finally distributed among the nine census regions:

$$QMILTR_{IF,REG} = MFD_{IF,T} * MILTRSHR_{IF,REG} \quad (150)$$

where:

QMILTR = Regional fuel consumption, by fuel type, in Btu
MILTRSHR = Regional consumption shares, from 1991 data, held constant

3F-2. Mass Transit Demand Model

The growth of passenger-miles in each mode of mass transit is assumed to be proportional to the growth of passenger-miles in light duty vehicles. This is determined from the output of the VMT module and the load factor for LDV's, held constant at 1989 levels:

$$TMOD_{1,T} = VMTEE_T * TMLOAD89_1$$

and:

$$TMOD_{IM,T} = TMOD_{IM,T-1} * \left[\frac{TMOD_{1,T}}{TMOD_{1,T-1}}\right]^{BETAMS} \quad (151)$$

where:

TMOD = Passenger-miles traveled, by mode
VMTEE = LDV vehicle-miles traveled, from the VMT module
TMLOAD89 = Average passengers per vehicle, by mode (1=LDV's)
BETAMS = Coefficient of proportionality, relating mass transit to LDV travel
IM = Index of transportation mode: 1 = LDV's, 2-4 = Buses, 5-7 = Rail

Fuel efficiencies, in Btu per vehicle-mile, are obtained from the Freight Module for buses and rail; and mass transit efficiencies, in Btu per passenger-mile, are calculated:

$$TMEFFL_{IM,T} = \frac{\left[TMEFF89_{IM} * \left(\frac{FMPG_{TYPE,T}}{FMPG89_{TYPE}}\right)\right]}{TMLOAD89_{IM}} \quad (152)$$

where:

TMEFFL = Btu per passenger-mile, by mass transit mode
TMEFF89 = Base-year Btu per vehicle-mile, by mode
FMPG = Fuel efficiency, by vehicle type, from the Freight Module
FMPG89 = Base-year fuel efficiency, by vehicle type, from the Freight Module
TYPE = Vehicle type, from the Freight Module: 1 = Mid-size trucks, 2 = Rail

Total fuel consumption may then be calculated and distributed among regions according to their populations:

$$QMODR_{IM,IR,T} = TMOD_{IM,T} * TMEFFL_{IM,T} * \left[\frac{TMC_POPAFO_{IR,T}}{\sum_{IR=1}^{9} TMC_POPAFO_{IR,T}}\right] \quad (153)$$

where:

QMODR = Regional consumption of fuel, by mode
TMC_POPAFO = Regional population forecasts, from the Macro Module

3F-3. Recreational Boating Demand Model

The growth in fuel use by recreational boats is considered to be proportional to the growth in disposable personal income:

$$RECFD_T = RECFD_{T-1} * \left[\frac{TMC_YD_T}{TMC_YD_{T-1}} \right]^{BETAREC} \quad (154)$$

where:

RECFD = National recreational boat gasoline consumption in year T
TMC_YD = Total disposable personal income, from the Macro Module
BETAREC = Coefficient of proportionality relating income to fuel demand for boats

Regional consumption is calculated according to population, as with mass transit, above:

$$QRECR_{IR,T} = RECFD_T * \left[\frac{TMC_POPAFO_{IR,T}}{\sum_{IR=1}^{9} TMC_POPAFO_{IR,T}} \right] \quad (155)$$

where:

QRECR = Regional fuel consumption by recreational boats in year T

3F-4. Lubricant Demand Model

The growth in demand for lubricants is considered to be proportional to the growth in highway travel by all types of vehicles. Total highway travel is first determined:

$$HYWAY_T = VMTEE_T + FTVMT_T + FLTVMT_T \quad (156)$$

where:

HYWAY = Total highway VMT
FTVMT = Total freight truck VMT, from the Freight Module
FLTVMT = Total fleet vehicle VMT, from the Fleet Module

Lubricant demand is then estimated:

$$LUBFD_T = LUBFD_{T-1} * \left[\frac{HYWAY_T}{HYWAY_{T-1}}\right]^{BETALUB} \quad (157)$$

where:

LUBFD = Total demand for lubricants in year T

BETALUB = Constant of proportionality, relating highway travel to lubricant demand

Regional allocation of lubricant demand is finally determined by regional weighting of all types of highway travel:

$$QLUBR_{IR,T} = LUBFD_T * \left[\frac{\left(\left(VMTEE_T + FLTVMT_T\right) * SHRMG_{IR,T}\right) + \left(FTVMT_T * SHRDS_{IR,T}\right)}{HYWAY_T}\right] \quad (158)$$

where:

QLUBR = Regional demand for lubricants in year T, in Btu

SHRMG = Regional share of motor gasoline consumption, from SEDS

SHRDS = Regional share of diesel consumption, from SEDS

Figure 3F-2. Military Demand Model

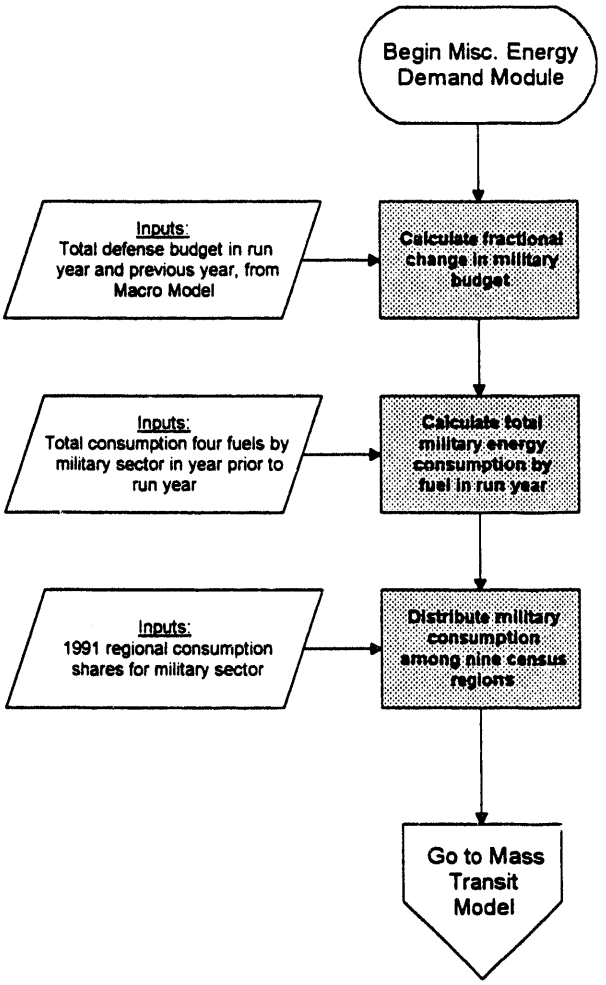


Figure 3F-3. Mass Transit Demand Model

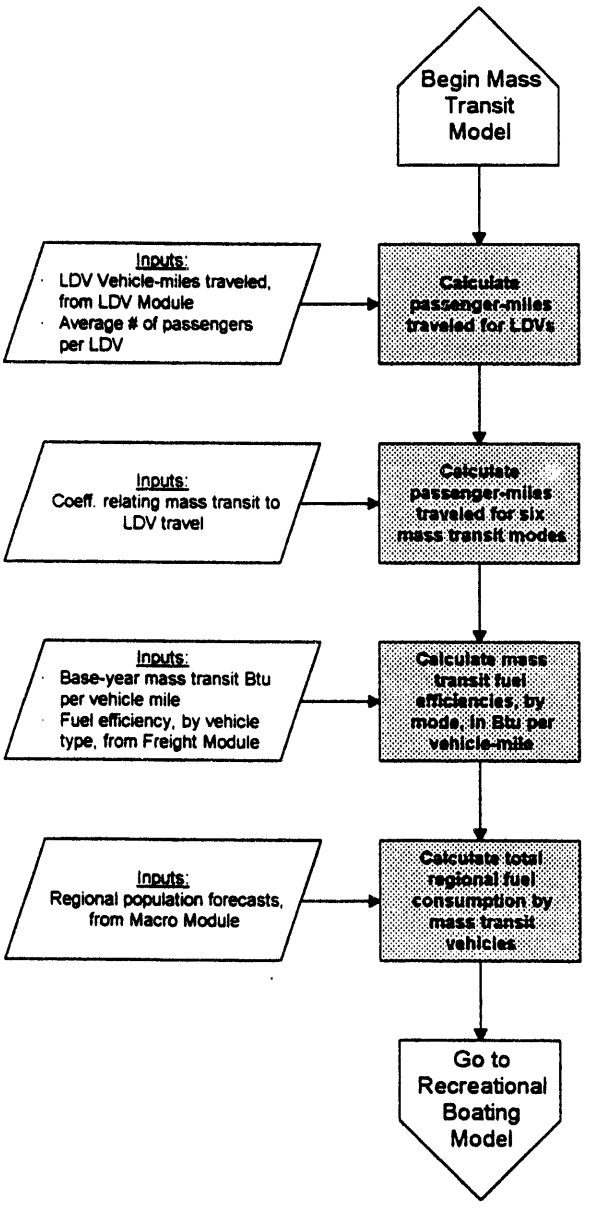


Figure 3F-4. Recreational Boating Demand Model

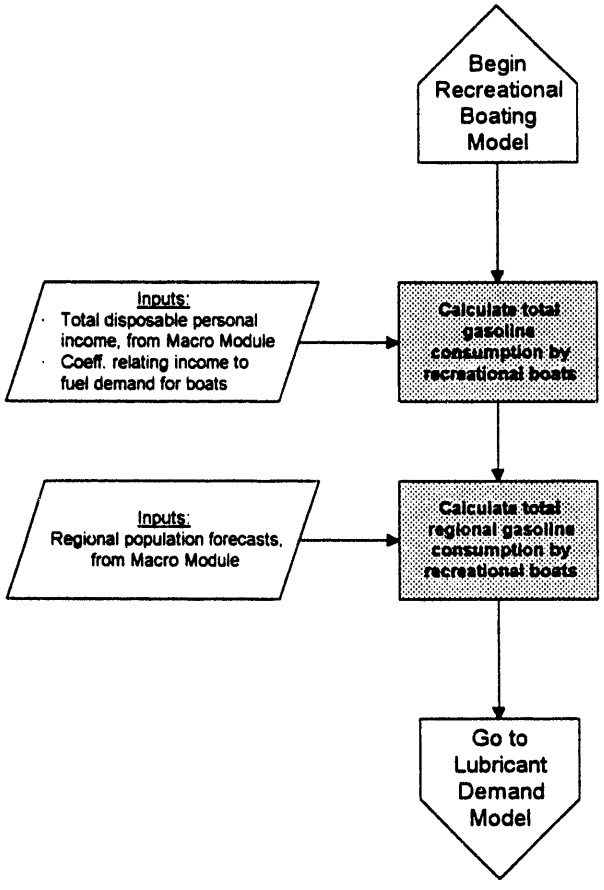
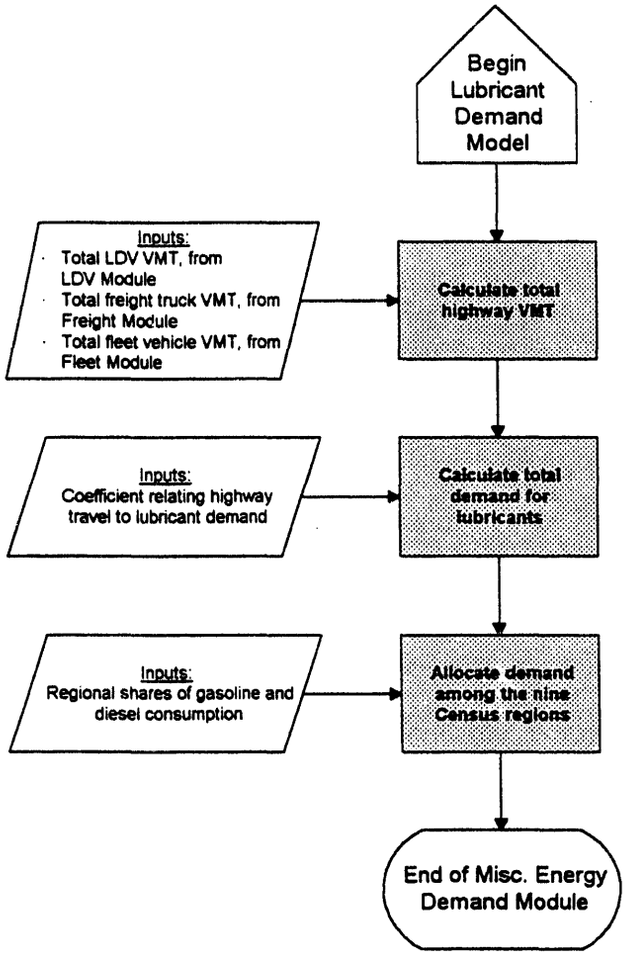


Figure 3F-5. Lubricant Demand Model



3G. Vehicle Emissions Module

RATIONALE

Vehicular emissions at the national level account for roughly two-fifths of total Carbon and NO_x emissions. This importance is reflected in the prominent role vehicles have in the Clean Air Act Amendment of 1990 (CAA90). This module reports vehicular emissions based on both the mix of vehicle technologies utilized over time, and the age distribution of these vehicles. This is a significant improvement over the predecessor model, which does not keep track of the level of emissions associated with vehicles. In NEMS, emissions from new, conventionally powered, light-duty vehicles decline over time in accordance with the provisions of the CAA90. Emissions may decline even further as alternative sources of energy and new technologies are utilized by light-duty vehicles. Direct emissions from battery-powered vehicles, for example, are zero. Specific pollutants addressed in this module include SO_x, NO_x, total Carbon, CO_2, CO, and Volatile Organic Compounds (VOC).

MODEL STRUCTURE

The solution algorithm consists of multiplying levels of travel by appropriate average emission factors for each mode of travel. Emission factors depend on the mix of technologies and fuels utilized within a mode. For example, the emission factor used for light-duty vehicles depends on the miles traveled utilizing each light-duty vehicle technology and fuel combination (see chapter 2). Even if no change occurs in the mix of technologies utilized in light-duty vehicles, emissions per vehicle-mile traveled will decline in the forecast as more stringent standards are phased in and older more polluting vehicles leave the fleet. It should be noted that the emissions factors implicitly reflect the effect of fuel efficiency improvements on carbon (including CO and CO_2) emissions and assume the compliance with increasingly stringent standards concerning other criteria pollutants. In the equation below, light-duty vehicle and freight truck emissions are estimated in units of grams of pollutant per mile of travel to be consistent with the definitions of vehicle emission standards.

$$\mathbf{EMISS}_{IE,IM,IR,T} = \mathbf{EFACT}_{IE,IM,IR,T} * \mathbf{U}_{IM,IR,T} \qquad \textbf{(159)}$$

where:

EMISS = Regional emissions of a given pollutant, by mode of travel

EFACT = Emissions factor relating measures of travel to pollutant emissions

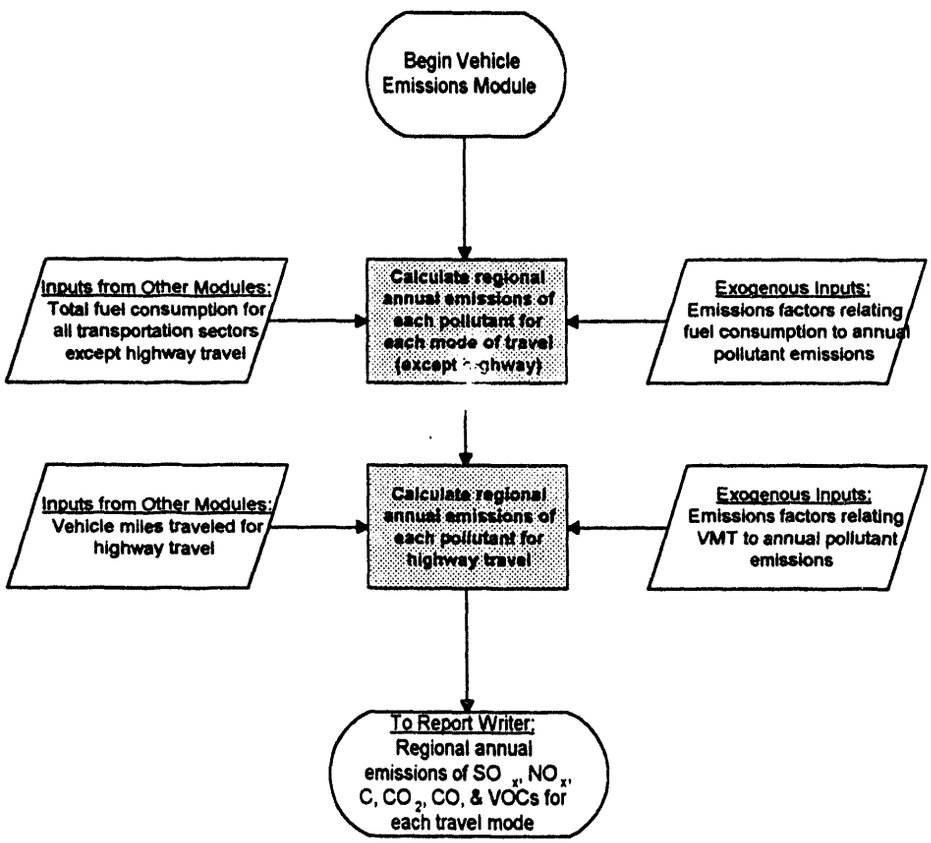
U = Measure of travel demand, by mode: units in VMT for highway travel, gallons of fuel consumption for other modes

IM = Index of travel mode: references individual vehicle types used in the preceding modules

IE = Index of pollutants: 1 = SO_x, 2 = NO_x, 3 = C, 4 = CO_2, 5 = CO, 6 = VOC
IR = Index identifying census region

The development of the emissions factors is documented in Appendix F, Attachment 6.

Figure 3G-1. Vehicle Emissions Module



4. MAJOR ASSUMPTIONS

Overview

This section reveals the key underlying assumptions that are critical to the generation of the base case and four side cases. These sets of assumptions discuss the following issues: technology penetration, environmental legislation, efficiency standards, and other important drivers for the transportation demand model. The NEMS transportation model estimates energy consumption across the nine census regions and over ten fuel types. Each fuel type is modeled according to fuel-specific technology attributes applicable by transportation mode. Total energy consumption is modeled by seven aggregate modes of transport: light-duty vehicles (cars, light trucks, and vans), freight trucks, freight and passenger airplanes, freight rail, freight shipping, mass transit, and miscellaneous transport. Light-duty vehicle fuel consumption is further sub-divided into personal usage, and commercial fleet consumption.

Inputs From NEMS Macro Model

Macroeconomic sector inputs used in the NEMS Transportation Model consist of the following: Gross Domestic Product, industrial output by SIC code, personal disposable income, new car and light truck sales, total population, driving age population, total value of imports and exports, and the military budget.

Table 4-1. Macroeconomic Inputs to the Transportation Model

Macroeconomic Input	1990	1995	2000	2005	2010
New Car Sales (mil)	9.51	9.27	9.76	10.12	10.41
New Light Truck Sales (mil)	4.39	5.27	5.65	6.29	6.51
Driving Age Population (mil)	192.7	202.1	212.8	223.8	235.4
Total Population (mil)	250.3	263.6	275.6	287.1	298.9

Source: Energy Information Administration, AEO94 Forecasting System runs AEO94B.D1221934.

Light-Duty Vehicle Module

Fuel Economy Model

The fuel economy model utilizes 52 new technologies for each size class based on the cost-effectiveness of each technology, and an initial availability year. The discounted stream of fuel savings are compared to the marginal cost of each technology. The fuel economy module assumes the following:

- 4 year payback period on all fuel saving technologies.
- 10% real discount rate.
- Corporate Average Fuel Economy (CAFE) standards remain constant at 1993 levels.
- Expected future fuel prices are calculated based on an extrapolation of the growth rate between fuel prices three years and five years prior to the present year. This assumption is founded upon an assumed lead time of three to five years to significantly modify the vehicles offered by a manufacturer.
- Degradation factors used to convert EPA rated fuel economy to actual "on the road" fuel economy, are based on application of a logistic curve to the projections of three factors: increase in city/highway driving, higher congestion levels, and rising highway speeds.[46, 47] Automobile and light truck degradation factors are assumed to be the same over time.

Regional Sales Model

The vehicle sales share section holds vehicle sales shares by import and domestic manufacturers constant within a vehicle size class benchmarked to 1990 Oak Ridge National Laboratory data.[48]

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[46] Maples, John D., "The Light-Duty Vehicle MPG Gap: It's Size Today and Potential Impacts in the Future," University of Tennesee Transportation Center, Knoxville, TN, May 28, 1993, Draft.

[47] Decision Analysis Corporation of Virginia, "Fuel Efficiency Degradation Factor," Final Report, Subtask 1, prepared for: Energy Information Administration, August 3, 1992.

[48] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 13, March 1993.

Table 4-2. Car and Light Truck Fuel Economy Degradation Factors

1990	2000	2005	2010
.854	.832	.823	.817

Source: Decision Analysis Corporation of Virginia, "Fuel Degradation Factor," Final Report, Subtask 1, prepared for: Energy Information Administration, August 3, 1992.

Alternative-Fuel Vehicle Model

The alternative-fuel technology choice model utilizes a discrete choice specification, which uses vehicle attributes as inputs, and forecasts vehicle sales shares among the following sixteen light-duty technologies: gasoline internal combustion engine (ICE), diesel ICE, ethanol flex, ethanol neat, methanol flex, methanol neat, electric dedicated (only uses electricity), electric hybrid with large ICE, electric hybrid with small ICE, electric hybrid with gas turbine, compressed natural gas (CNG), liquid petroleum gas (LPG), gas turbine gasoline, gas turbine CNG, fuel cell methanol, and fuel cell liquid hydrogen. Listed below are a few examples of the inputs variables that correspond to the vehicle attributes used in the analysis. With the exception of vehicle fuel economy, all other attributes are exogenously set based on offline analysis.[49]

Vehicle attributes vary by three size classes, and fuel availability varies by census division. However, all vehicle attributes correspond to prototype vehicles. It is assumed that once the logit model estimates future sales shares, these shares are applicable to both cars and light trucks. Vehicle prices are assumed to represent mass production prices. All alternative-fuel vehicle fuel efficiencies are calculated relative to conventional gasoline MPG. It is assumed that fuel efficiency improvements to conventional vehicles will be transferred to alternative-fuel vehicles.[50] Specific individual alternative-fuel technological improvements are handled separately by varying the fuel efficiency index over time. Commercial availability estimates are assumed values according to a logistic curve based on the initial technology introduction date, and were constructed in cooperation with the DOE Office of Efficiency and Renewable Energy. Model coefficients summarizing consumer valuation of vehicle attributes were derived from a stated preference survey conducted in California, and are assumed to be representative of the U.S.

[49] Science Applications International Corporation, "Alternative-Fuel Vehicle Module Database," Draft Report, Subtask 4, Prepared for Energy Information Administration, September 15, 1992.

[50] Energy and Environmental Analysis, K.G. Duleep, intial coefficients for alternative-fuel vehicles relative to conventional were used from the Department of Energy, Office of Policy Analysis IDEAS Model.

Table 4-3. Alternative-Fuel Vehicle Attributes For Three-Stage Logit Model

		Small Vehicle Size Class					
		Gasoline	Ethanol Flex	Methanol Flex	CNG	Electric Vehicle Hybrid	Dedicated Electric Vehicle
Vehicle Price (1990 $)	1990	$8,200	$12,700	$12,900	$10,950	$58,200*	$53,200 *
	2010	$12,180	$12,850	$13,050	$13,230	$22,800*	$22,340*
Vehicle MPG Relative to Gasoline	1990	1.000	1.055	1.095	0.960	1.419	1.541
	2010	1.000	1.060	1.130	0.950	1.380	1.520
Vehicle Range (miles)	1990	350	260	220	225	225	108
	2010	427	317	268	275	305	146
Fuel Availa-bility Relative to Gasoline	1990	1.00	0.01	0.01	0.01	0.05	0.05
	2010	1.00	0.06	0.06	0.06	1.00	1.00
Emission Level Relative to Gasoline	1990	1.00	0.73	0.60	0.51	0.16	0.00
	2010	1.00	1.19	1.27	0.87	1.71	0.01
Commercial Availability Relative to Gasoline	1990	1.00	0.00	0.01	0.00	0.01	0.00
	2010	1.00	0.25	0.50	0.06	0.81	0.09

* Electric vehicle battery replacement cost included.

Source: Science Applications International Corporation, "Alternative-Fuel Vehicle Module Database," Draft Report, Subtask 4, Prepared for the Energy Information Administration, September 15, 1992.

The Low Emission Vehicle Program (LEVP) which began in California, has now been instituted in New York and Massachusetts. The following Zero Emission Vehicle (ZEV) and Ultra Low Emission Vehicle (ULEV) sales numbers come from the California Air Resource Board.[51] In the low world oil price case and the base case scenarios, only the ZEV sales shares are used. With

[51] California Air Resources Board, "Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Staff Report," August 13, 1990.

the high world oil price scenario, the ZEV and one half of the ULEV sales shares are included. Only half of the ULEV sales were included, because there is uncertainty with respect to meeting the ULEV air standards with reformulated gasoline and a heated catalytic converter. The AFV model compares these legislative mandated sales to the results from the alternative-fuel vehicle logit market driven sales shares. The legislative mandated sales serve as a minimum constraint to alternative-fuel vehicle sales.

Table 4-4. California Low Emission Vehicle Program Sales Mandates (Percentage of all LDV Sales)

	Ultra Low Emission Vehicles (ULEV)	Zero Emission Vehicles (ZEV)
1997	2%	-
1998	2%	2%
1999	2%	2%
2000	2%	2%
2001	5%	5%
2002	10%	5%
2003	15%	10%

Source: California Air Resources Board, "Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Staff Report," August 13, 1990.

Light Duty Vehicle Stock Module

Vehicle-Miles Traveled Model

The vehicle-miles traveled (VMT) model forecasts VMT as a function of the cost of driving per mile, income per capita, ratio of female to male VMT, and age distribution of the driving population. The ratio of female to male VMT is assumed to asymptotically approach 72 percent by 2010. Total VMT is calibrated to Federal Highway Administration (FHWA) VMT data.[52]

[52] U.S. Department of Transportation, Federal Highway Administration, Highway Statistics 1990, FHWA-PL-91-003, 1990.

Light Duty Vehicle Fleet Module

With the current focus of transportation legislation on commercial fleets and their composition, the NEMS Transportation Model has been designed to divide commerical fleets into three types of fleets: business, government, and utility. Based on this classification, commercial fleet vehicles vary in survival rates and duration in the fleet, before being folded back into the personal vehicle stock.

Sales shares of fleet vehicles by fleet type remain constant over the forecast period. Automobile fleets are divided into the following shares: business (85.59%), government (7.09%), and utilities (7.27%). Both car (23.17%) and light truck (13.95%) fleet sales are assumed to be a constant fraction of total vehicle sales.[53]

Alternative-fuel shares of fleet sales by fleet type are initially set according to historical shares, then compared to a minimum constraint level of sales based on legislative initiatives such as the Energy Policy Act, and the Low Emission Vehicle Program.[54, 55] Size class sales of alternative-fuel and conventional vehicles are held constant at historical levels.[56]

Individual sales shares of alternative-fuel fleet vehicles by technology type are assumed to remain at historical levels for utility and government fleets, but vary for business fleets in accordance with the technology shares applied in the personal vehicle stocks. Annual VMT per vehicle by fleet type stays constant over the forecast period based on ORNL fleet data. Fleet fuel economy for both conventional and alternative-fuel vehicles are assumed to be the same as the personal vehicle new vehicle fuel economy, and is subdivided into three size classes.

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[53] Oak Ridge National Laboratory, Fleet Vehicles in the United States: Composition, Operating Characteristics, and Fueling Practices, Prepared for Department of Energy, Office of Transportation Technologies, and Office of Policy, Planning, and Analysis, March 1992.

[54] U.S. Department of Energy, Office of Domestic and International Energy Policy, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Technical Report Ten: Analysis of Alternative-Fuel Fleet Requirements," May 1992.

[55] California Air Resources Board, "Proposed Regulations for Low-Emission Vehicles and Clean Fuels, Staff Report," August 13, 1990.

[56] Oak Ridge National Laboratory, Fleet Vehicles in the United States: Composition, Operating Characteristics, and Fueling Practices, Prepared for Department of Energy, Office of Transportation Technologies, and Office of Policy, Planning, and Analysis, March 1992.

Table 4-5. Commercial Fleet Size Class Shares By Fleet and Vehicle Type

Fleet Type by Size Class	Automobiles	Light Trucks
Business Fleet		
Small	4.55	37.34
Medium	71.59	37.90
Large	23.86	24.76
Government Fleet		
Small	4.35	21.34
Medium	56.52	44.39
Large	39.13	34.27
Utility Fleet		
Small	16.67	30.03
Medium	70.00	38.51
Large	13.33	31.46

Source: Oak Ridge National Laboratory, Fleet Vehicles in the United States: Composition, Operating Characteristics, and Fueling Practices, Prepared for the Department of Energy, Office of Transportation Technologies, and Office of Policy, Planning, and Analysis, March 1992.

Fleet alternative-fuel vehicle sales necessary to meet the Energy Policy Act of 1992 (EPACT) regulations, come from the DOE Office of Domestic and International Energy Policy.[57] Total projected alternative-fuel vehicle sales are divided into fleets by government, utility, business, and fuel providers. The business fleets represent one half of the DOE Office of Policy Analysis estimate, because it is assumed that only half of the business fleets are capable of being centrally fueled (re-fueled at the same location) as required by EPACT. Although inclusion of the business fleet is dependent upon a ruling making by the Secretary of Energy, the assumption is that fuel displacement goals set in EPACT can only be reached by inclusion of the business fleet.

[57] U.S. Department of Energy, Office of Domestic and International Energy Policy, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Technical Report Ten: Analysis of Alternative-Fuel Fleet Requirements," May 1992.

Table 4-6. EPACT Alternative-Fuel Vehicle Fleet Sale Estimates

	1990	1995	2000	2005	2010
Automobiles					
State & Local Gov't	0	0	0	85,538	92,149
Federal Gov't	0	5,000	10,692	13,365	13,365
Business	0	64,637	69,633	405,826	437,189
Fuel Provider	0	129,274	139,265	150,028	161,623
Light Trucks					
State & Local Gov't	0	0	0	19,612	21,128
Federal Gov't	0	5,000	10,692	13,365	13,365
Business	0	32,319	34,816	94,612	101,924
Fuel Provider	0	64,637	69,632	75,014	80,811

Source: U.S. Department of Energy, Office of Domestic and International Energy Policy, "Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector, Technical Report Ten: Analysis of Alternative-Fuel Fleet Requirements, May 1992.

Air Travel Module

Air Travel Demand Model

The air travel demand model calculates the ticket price for travel as a function of fuel cost and other operating costs. Non-fuel operating costs are assumed to remain constant across the forecast horizon.[58] A demographic index based on the propensity to fly was introduced into the air travel demand equation.[59] The propensity to fly was made a function of the age and sex group distribution over the forecast period.[60, 61] The air travel demand module assumes that these

[58] U.S. Department of Transportation, Research and Special Programs Administration, Air Carrier Financial Statistics Quarterly and Monthly, December 1990/1989, and prior issues.

[59] Transportation Research Board, Forecasting Civil Aviation Activity: Methods and Approaches, Appendix A, Transportation Research Circular Number 372, June 1991.

[60] Decision Analysis Corporation of Virginia, Proposed Methodology For Projecting Air Transportation Demand, Final Report, Subtask 2, July 8, 1992.

relationships between the groups and their propensity to fly remain constant over time. International revenue passenger miles is a fixed percentage of domestic revenue passenger miles based on historical data.[62] Load factors, represented as the average number of passengers per airplane, are assumed to remain constant over the forecast period.

Aircraft Fleet Efficiency Model

The aircraft fleet efficiency model consists of a stock model of both wide and narrow body planes by vintage. The shifting of passenger load between narrow and wide body aircraft takes place at a constant historical annual one percent rate.[63] The available seat-miles per plane, which measures the carrying capacity of the airplanes by aircraft type, remains constant and is based on holding the following constant within an aircraft type: airborne hours per aircraft per year, average flight speed, and the number of seats per aircraft.

The difference between the seat-miles demanded and the available seat-miles represent newly purchased aircraft. Aircraft purchases in a given year cannot change above historical annual growth rates, which sets an upper limit on the application of new aircraft to meet the gap between seat-miles demanded and available seat-miles. With a constraint on new aircraft purchases, it is assumed that when the gap exceeds histiorical aircraft sales levels planes that have been temporarily stored or retired will be brought back into service. Technological availability,

Table 4-7. Constant Available Seat-Miles Assumptions By Aircraft Type

Seat-Mile Variable	Narrow Body Aircraft	Wide-Body Aircraft
Airborne Hrs./Aircraft per yr.	2,383	3,336
Average Flight Speed (mph)	400	485
Number of Seats/Aircraft	126	296

Source: Federal Aviation Administration, FAA Aviation Forecasts, fiscal years 1991-2002, FAA-APO 90-1, and previous editions.

[61] Air Transport Association of America, Air Travel Survey, Washington D.C., 1990.

[62] U.S. Department of Transportation, U.S. International Air Travel Statistics, Transportation Systems Center, Cambridge, MA, annual issues.

[63] U.S. Department of Transportation, Federal Aviation Administration, FAA Aviation Forecasts Fiscal Years 1993-2004, February 1993.

economic viability, and efficiency characteristics of new aircraft are based on the technologies listed in the Oak Ridge National Laboratory Air Tranportation Energy Model.[64, 65] Fuel efficiency of new aircraft acquisitions represent at a minimum, a five percent improvement over the stock efficiency of surviving airplanes.[66] Maximum growth rates of fuel efficiency for new aircraft are based on a future technology improvement list based on an estimate of the introduction year, jet fuel price, and an estimate of the projected marginal fuel efficiency improvement.

Regional shares of all types of aircraft fuel are assumed to be constant, and are consistent with the State Energy Data Report estimate of regional jet fuel shares.[67]

Freight Transport Module

Highway Freight Model

The freight truck model converts industrial output in dollar terms to an equivalent measure of volume by using a freight adjustment coefficient. These freight truck adjustment coefficients vary by industrial SIC code, but remain constant over time, and are estimated from historical freight data.[68, 69] Freight truck load factors (ton-miles per truck) by SIC code are constants formulated from historical load factors.[70] Growth of VMT in the retail sector is assumed to be proportional to growth in total industrial output. Growth of VMT in the construction sector is assumed to be proportional to the growth in total disposable income. All freight trucks are subdivided into light, medium, medium-heavy, and heavy-duty trucks. Freight truck fuel efficiency growth rates

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[64] Oak Ridge National Laboratory, Energy Efficiency Improvement of Potential Commercial Aircraft to 2010, ORNL-6622, June 1990.

[65] Oak Ridge National Laboratory, Air Transport Energy Use Model, April 1991, Draft.

[66] U.S. Department of Transportation, Federal Aviation Administration, FAA Aviation Forecasts Fiscal Years 1993-2004, February 1993.

[67] Department of Energy, Energy Information Administration, State Energy Demand Survey, May 1993.

[68] Decision Analysis Corporation of Va., Freight Transportation Requirements Analysis For The NEMS Transportation Sector Model, Subtask 5, Prepared for Energy Information Administration, August 3, 1992.

[69] Reebie Associates, TRANSEARCH Freight Commodity Flow Database, Greenwich, Connecticutt.

[70] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 13, March 1993.

Table 4-8. Future New Aircraft Technology Improvement List

Proposed Technology	Year of Intro-duction	Jet Fuel Price Necessary For Cost-Effectiveness (87$/Gal)	Seat-Miles per Gallon (SMPG) Gain Over 1990's	
			Narrow Body	Wide Body
ENGINES				
Ultra-high Bypass	1995	$0.69	10%	10%
Propfan	2000	$1.36	23%	0%
AERODYNAMICS				
Hybrid Laminar Flow	2020	$1.53	15%	15%
Advanced Aerodynamics	2000	$1.70	18%	18%
OTHER				
Weight Reducing Materials	2000	-	15%	15%
Thermodynamics	2010	$1.22	20%	20%

Source: Greene, D.L., Energy Efficiency Improvement Potential of Commercial Aircraft to 2010, ORNL-6622, 6/1990., and from data tables in the Air Transportation Energy Use Model (ATEM), Oak Ridge National Laboratory.

relative to fuel prices are tied to historical growth rates by size class.[71] VMT freight estimates by size class and technology are based on historical growth rates. Fuel consumption by freight trucks is regionalized according to the State Energy Data System 1991 distillate regional shares.[72]

Rail Freight Model

The rail freight model receives industrial output by SIC code measured in real 1987 dollars and converts these dollars into an adjusted volume equivalent. Rail freight adjustment coefficients, which are used to convert dollars into volume equivalents, remain constant and are based on

[71] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 13, March 1993.

[72] U.S. Department of Energy, Energy Information Administration, State Energy Demand Report 1991, May 1993.

historical data.[73, 74] Initial rail freight fuel efficiencies are based on the freight model from Argonne National Laboratory.[75] The distribution of rail fuel consumption by fuel type remains constant and is based on historical data.[76] Regional freight rail consumption estimates are distributed according to the State Energy Data Report 1991.[77]

Waterborne Freight Model

The waterborne freight model also converts industrial output by SIC code measured in dollars, to a volumetric equivalent by SIC code.[78] These freight adjustment coefficients are based on analysis of historical data[79], and remain constant throughout the forecast period. Domestic shipping efficiencies are based on the freight model by Argonne National Laboratory.[80] The distribution of domestic and international shipping fuel consumption by fuel type remains constant throughout the analysis, and is based on historical data.[81] Regional domestic and international shipping consumption estimates are distributed according to the State Energy Data Report 1991 residual oil regional shares.[82]

Emissions Module

The NEMS Transportation model uses the same emissions coefficients by fuel type that are contained in the Industrial Sector Module Assumptions section.

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[73] Decision Analysis Corporation of Va., Freight Transportation Requirements Analysis For The NEMS Transportation Sector Model, Subtask 5, Prepared for Energy Information Administration, August 3, 1992.

[74] U.S. Department of Transportation, Federal Railroad Administration, 1989 Carload Waybill Statistics; Territorial Distribution, Traffic and Revenue by Commodity Classes, September 1991 and prior issues.

[75] Argonne National Laboratory, Transportation Energy Demand Through 2010, 1992.

[76] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 13, March 1993.

[77] Department of Energy, Energy Information Administration, State Energy Demand Survey, May 1993.

[78] Decision Analysis Corporation of Va., Freight Transportation Requirements Analysis For The NEMS Transportation Sector Model, Subtask 5, Prepared for Energy Information Administration, August 3, 1992.

[79] Army Corp of Engineers, Waterborne Commerce of the United States, Waterborne Statistics Center, New Orleans, La., 1991.

[80] Argonne National Laboratory, Transportation Energy Demand Through 2010, 1992.

[81] Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 13, March 1993.

[82] Department of Energy, Energy Information Administration, State Energy Demand Survey, May 1993.

Table 4-9. Distribution of Rail Fuel Consumption By Fuel Type

	Diesel Fuel	Electricity
FREIGHT	100%	0%
PASSENGER:		
Transit	0%	100%
Commuter	34%	66%
Intercity	73%	27%

Source: Oak Ridge National Laboratory, Transportation Energy Databook: Edition 13, March 1993.

Appendix A. Input Data and Parameters

LIST OF TABLES

Table A-1. List of Transportation Sector Model Variables A-1
LIGHT DUTY VEHICLE MODULE A-1
Fuel Economy Model A-1
Regional Sales Model A-4
Alternative Fuel Vehicle Model A-5
LIGHT DUTY VEHICLE STOCK MODULE A-8
LIGHT DUTY VEHICLE FLEET MODULE A-12
AIR TRAVEL MODULE A-15
Air Travel Demand Model A-15
Aircraft Fleet Efficiency Model A-16
FREIGHT TRANSPORT MODULE A-18
MISCELLANEOUS ENERGY DEMAND MODULE A-21
TRANSPORTATION EMISSIONS MODULE A-22

Table A-2. Light Duty Vehicle Market Classes A-25

Table A-3. Maximum Light Duty Vehicle Market Penetration Parameters A-26

Table A-4. Aircraft Fleet Efficiency Model Adjustment Factors A-27

Table A-5. List of Expected Aircraft Technology Improvements A-28

Table A-1. List of Transportation Sector Model Variables

The following table itemizes the variables, data inputs, parameters, and indices employed in each of the Transportation Model's constituent components. These variables are grouped by module, and are identified by the equation number in Appendix B in which they are first encountered. The sources of parameters and data inputs are provided immediately following this table.

LIGHT DUTY VEHICLE MODULE: Fuel Economy Model					
ITEM	**CLASS. (Source)**	**DESCRIPTION**	**UNITS**	**SUBROUTINE**	**EQ #**
ACTUALSMKT	Variable	The economic share of technology *iic*, prior to consideration of engineering or regulatory constraints.	Percent	FEMCALC	7
ADJFE	Variable	The fuel economy adjustment factor	Percent	FEMCALC	21
ADJHP	Variable	The fractional change in horspower from the previous year within a given vehicle class	Percent	FEMCALC	19
BENCHMPG	Input Data (B)	MPG benchmark factors to ensure congruence with most recent data from ORNL	–	FEMSIZE	39
CAFE	Variable	Actual CAFE values by group	Miles per Gallon	CAFECALC	34
CLASSSSHARE	Variable	Relative market share for each class. Basis for CAFE calculations	Percent	CAFECALC	31
CMKS	Variable	Class market share, subsequently reassigned to the appropriate vehicle class and group, $CLASSSSHARE_{icl,igp}$	Percent	CMKSCALC	32
COSTEFFECT	Variable	A unitless measure of cost effectiveness	–	FEMCALC	6
DELSCOSTABS	Variable	Change in cost associated with technology *iic*	Percent	FEMCALC	4
DELSCOSTWGT	Variable	The weight-based change in cost of technology *iic*	$ per lb	FEMCALC	4
DELSFE	Variable	The fractional change in fuel economy associated with technology *iic*	Percent	FEMCALC	3
DELSHP	Variable	The fractional change in horsepower of technology *iic*	Percent	FEMCALC	5
DELSMKT	Variable	The amount of the superseded technology's market share to be removed	Percent	NOTESSUPER	26
DELSWGTABS	Variable	The change in weight associated with technology *iic*	lbs	FEMCALC	16
DELSWGTWGT	Variable	The fractional change in weight associated with technology *iic*	Percent	FEMCALC	4
DELTASMKT	Variable	The change in market share for technology *iic*	Percent	FEMCALC	14
DIFFSLN	Variable	The increment from the base year (1990) of the log of the market share ratio	–	CMKSCALC	29

LIGHT DUTY VEHICLE MODULE: Fuel Economy Model					
ITEM	CLASS. (Source)	DESCRIPTION	UNITS	SUBROUTINE	EQ #
DISCOUNT	Parameter (A)	Discount rate used in payback calculation	Percent	FEMCALC	3
FE	Variable	Fuel economy of technology *iic*, within seven size classes	Miles per Gallon	FEMCALC	3
FEMPG	Variable	Average fuel economy by six ORNL size classes	MPG	FEMSIZE	38
FESIXC	Variable	Fuel economy for cars within six size classes	MPG	FEMSIZE	40
FESIXT	Variable	Fuel economy for light trucks within six size classes	MPG	FEMSIZE	40
FUELCOST	Variable	Projected fuel cost	$ per MMBtu	FEMCALC	1
FUELSAVE	Variable	The expected present value of fuel savings over the payback period	$	FEMCALC	3
HP	Variable	Horsepower	HP	FEMCALC	18
icl	Index	FEM vehicle size class index (7)	–	FEMSIZE	–
igp	Index	CAFE group index: 1 = domestic car, 2 = import car, 3 = domestic light truck, 4 = import light truck	–	FEMSIZE	–
INCOME	Variable	Household income	$ per year	FEMCALC	198
ino	Index	The index identifying the technologies in the superseding group	–	NOTE$SUPER	–
isno	Index	An index indicating the superseded technology	–	NOTE$SUPER	–
iic	Index	The index representing the technology under consideration	–	FEMCALC	3
MANDMKSH	Input Data (A)	Mandatory market share	Percent	FEMCALC	9
MAP	Input Data (A)	Array of mapping constants, which converts FEM to ORNL size classes	–	FEMSIZE	35
MAPSALE	Variable	Disaggregate vehicle sales	Units	FEMSIZE	35
MAPSHR	Variable	Sales shares within the disaggregate array	Percent	FEMSIZE	37
MAX$SHARE	Input Data (A)	The maximum market share of the group, *ino*	Percent	NOTE$SUPER	25
MKT$MAX	Input Data (A)	Maximum market share of technology in given class	Percent	NOTE$SUPER	25
MKT$PEN	Variable	Market share of technology in given class and year	Percent	FEMCALC	8
MMAX	Variable	The maximum market share for technology *iic*, obtained from MKT$MAX	Percent	FEMCALC	7
N	Index	Time period index (1990 = 1)	–	FEMSIZE	–

LIGHT DUTY VEHICLE MODULE: Fuel Economy Model					
ITEM	**CLASS. (Source)**	**DESCRIPTION**	**UNITS**	**SUBROUTINE**	**EQ #**
num$sup	Index	The number of technologies in the superseding group	–	NOTE$SUPER	–
NVS7SC	Variable	New vehicle sales within the seven FEM size classes	Units	TSIZE	41
ORNLMPG	Input Data (B)	Most recent (1992) fuel economy data from ORNL	MPG	FEMSIZE	39
osc	Index	ORNL size class index (6)	–	FEMSIZE	–
PAYBACK	Input Data (A)	The user-specified payback period	Years	FEMCALC	3
PERFFACT	Input Data (A)	Performance factor (multiplier for horsepower adjustment)	–	FEMCALC	19
PMAX	Parameter (A)	The institutional maximum market share, which models tooling constraints on the part of the manufacturers	Percent	FEMCALC	7
PRICE	Variable	Vehicle price	$	FEMCALC	17*
PRICE$EX	Variable	The expected price of fuel	$	FEMCALC	2
PSLOPE	Variable	The fuel cost slope	–	FEMCALC	1
RATIO$LN	Variable	Log of the market share ratio of the considered vehicle class	–	CMKSCALC	31
REGCOST	Variable	A factor representing regulatory pressure to increase fuel economy	$ per MPG	FEMCALC	6
REQ$MKT	Input Data (A)	The total market share of those technologies which are required for the implementation of technology *itc*, indicating that technology's maximum share	Percent	FEMCALC	10
SYNR$DEL	Input Data (A)	The synergistic effect of two technologies on fuel economy	–	FEMCALC	13
TECHCOST	Input Data (A)	The cost of technology *itc*	$	FEMCALC	4
TOT$MKT	Variable	The total market share of the considered group of technologies	Percent	NOTE$SUPER	27
TOTNVS7	Variable	Total new vehicle sales within the six ORNL size classes	Units	FEMSIZE	36
VAL$PERF	Input Data (A)	The dollar value of performance of technology *itc*	$	FEMCALC	5
VALUEPERF	Variable	The value associated with an incremental change in performance	$	FEMCALC	5
WEIGHT	Variable	The base year vehicle weight, absent the considered technology	lbs	FEMCALC	4
YEAR	Index	Year index ($YEAR = N+1$)	–	FEMSIZE	–

LIGHT DUTY VEHICLE MODULE: Regional Sales Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
AHPCAR	Variable	Average automobile horsepower	HP	TSIZE	49
AHPTRUCK	Variable	Average light truck horsepower	HP	TSIZE	50
COMTSHR	Data Input (B)	Fraction of new light trucks dedicated to commercial freight	Percent	TSIZE	42
COSTMIR	Variable	The cost of driving in region *REG*	$ per Mile	TREG	52
DAF	Parameter (C)	A demographic adjustment factor, to reflect different age groups' driving patterns	–	TEXOG	55
FLTCRAT	Parameter (B)	Fraction of new cars purchased by fleets	Percent	TSIZE	41
FLTTRAT	Parameter (B)	Fraction of new light trucks purchased by fleets	Percent	TSIZE	42
GROUP	Index	Index indicating domestic or imported vehicles	–	TSIZE	–
HP	Variable	Vehicle horsepower by FEM size class, group	HP	TSIZE	47
HPCAR	Variable	Average horsepower of new automobiles, by size class *SC*	HP	TSIZE	47
HPTRUCK	Variable	Average horsepower of new light trucks, by size class *SC*	HP	TSIZE	48
INCOMER	Variable	Regional per capita disposable income	$	TREG	53
LTSHRR	Variable	Non-fleet market shares of light trucks, by size class *SC*	Percent	TSIZE	46
NCS	Variable	New car sales, by size class and region	Units	TREG	57
NCSTSCC	Variable	New car sales in the modified six size classes, *SC*	Units	TSIZE	43
NLTS	Variable	New light truck sales, by size class and region	Units	TREG	58
NLTSTSCC	Variable	New light truck sales in six size classes *SC*	Units	TSIZE	44
NVS7SC	Variable	New vehicle sales in the original seven FEM size classes	Units	TSIZE	43
PASSHRR	Variable	Non-fleet market shares of automobiles, by size class *SC*	Percent	TSIZE	45
PRFEM	Data Input (D)	Ratio of female to male driving rates	–	TVMT	54
RHO	Parameter (C)	Lag factor for the VMT difference equation	–	TVMT	54
RSHR	Variable	Regional VMT shares	Percent	TREG	57
SALESHR	Data Input (B)	Fraction of vehicle sales which are domestic/imported	Percent	TSIZE	41
SEDSHR	Variable	Regional share of the consumption of a given fuel in period *T*	Percent	TREG	51
TMC_POP16	Variable	Total regional population over the age of 16	–	TMAC	55

LIGHT DUTY VEHICLE MODULE: Regional Sales Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
TMC_POPAFO	Variable	Total population in region *REG*	–	TMAC	53
TMC_SQDTRUCK SL	Variable	Total light truck sales (supplied by the MACRO module)	Units	TMAC	42
TMC_SQTRCARS	Variable	Total new car sales (supplied by the MACRO module)	Units	TSIZE	41
TMC_YD	Variable	Estimated disposable personal income by region, *REG*	$	TMAC	51
VMT16R	Variable	Vehicle-miles traveled per population over 16 years of age	–	TREG	54
VMTEER	Variable	Total VMT in region *REG*	–	TREG	55

LIGHT DUTY VEHICLE MODULE: Alternative Fuel Vehicle Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
AFCOST	Variable	Alternative vehicle fuel price	$ per MMBtu	TALT3	60
APSHR11	Variable	Relative market shares of each aggregate technology	Percent	TALT1	76
APSHR22	Variable	Relative market shares of each AFV technology	Percent	TALT2	72
APSHR33	Variable	Relative market shares of each EV technology	Percent	TALT3	68
APSHR44	Variable	Absolute market shares of each technology	Percent	TALT1	79
BETACONST	Parameter (F)	Constant associated with each considered technology *IT*	–	TALT3	66
BETACONST1	Parameter (F)	Constant associated with each considered technology	–	TALT1	74
BETACONST2	Parameter (F)	Constant associated with each considered AFV technology	–	TALT2	70
BETAEM	Parameter (F)	Coefficient associated with vehicle emissions	–	TALT3	66
BETAEM2	Parameter (F)	Coefficient associated with the square of vehicle emissions	–	TALT3	66
BETAFA	Parameter (F)	Coefficient associated with fuel availability	–	TALT3	66
BETAFA2	Parameter (F)	Coefficient associated with the square of fuel availability	–	TALT3	66
BETAFC	Parameter (F)	Coefficient associated with fuel cost	$(\$)^{-1}$	TALT3	66
BETAVP	Parameter (F)	Coefficient associated with vehicle price	$(\$)^{-1}$	TALT3	66

LIGHT DUTY VEHICLE MODULE: Alternative Fuel Vehicle Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
BETAVR	Parameter (F)	Coefficient associated with vehicle range	$(Miles)^{-1}$	TALT3	66
BETAVR2	Parameter (F)	Coefficient associated with the square of vehicle range	$(Miles)^{-2}$	TALT3	66
COMAV	Input Data (E)	Commercial availability of each AFV technology	–	TALT3	59
COPCOST	Variable	Fuel operating costs for each AFV technology	Cents per Mile	TALT3	65
COPCOST1	Variable	Fuel operating costs for conventional and alternative vehicles	Cents per mile	TALT1	74
COPCOST2	Variable	Fuel operating costs for alternative vehicles	Cents per mile	TALT2	70
EMISS1	Input Data (E)	Emissions levels relative to gasoline ICE's	–	TALT1	74
EMISS2	Input Data (E)	AFV emissions levels relative to gasoline ICE's	–	TALT2	70
EMISS3	Input Data (E)	EV emissions levels relative to gasoline ICE's	Percent	TALT3	66
EVC1	Variable	Exponentiated value of vehicle utility vector	–	TALT1	75
EVC2	Variable	Exponentiated value of alternative vehicle utility vector	–	TALT2	71
EVC3	Variable	Exponentiated value of electric vehicle utility vector	–	TALT3	67
FAVAIL	Input Data (E)	Availability of each alternative fuel relative to gasoline	Percent	TALT3	60
FAVAIL11	Input Data (E)	Fuel availability for conventional and alternative technologies	Percent	TALT1	74
FAVAIL22	Input Data (E)	Alternative technology fuel availability	Percent	TALT2	70
FAVAIL33	Input Data (E)	Fuel availability for EV technologies	Percent	TALT3	66
FEC3SC	Variable	Automobile fuel economy within the three reduced size classes	MPG	TALT3	61
FET3SC	Variable	Light truck fuel economy within the three reduced size classes	MPG	TALT3	62
IT	Index	Index of the sixteen engine technologies considered by the model	–	TALT3	–
RFP	Variable	Regional fuel price	Dollars per MMBtu	TALT3	50
TTS0	Input Data (X)	The exogenously specified year in which 50% of the demand for technology *IT* can be met	Year	TALT3	59

LIGHT DUTY VEHICLE MODULE: Alternative Fuel Vehicle Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
VC1	Variable	Utility vector for conventional and alternative vehicles	–	TALT1	74
VC1	Variable	Utility vector for conventional and alternative vehicles	–	TALT1	74
VC2	Variable	Utility vector for alternative vehicles	–	TALT2	70
VC3	Variable	Utility vector for electric vehicles	–	TALT3	66
VEFF	Input Data (E)	Fuel economy of technology *IT*, relative to gasoline baseline	–	TALT3	64
VEFFACT	Variable	Baseline efficiency of gasoline ICE's, in MPG	Miles per MMBtu	TALT3	63
VPRICE1	Input Data (E)	Price of each considered technology in 1990$	1990 $	TALT1	74
VPRICE2	Input Data (E)	Price of each considered AFV technology in 1990$	1990 $	TALT2	70
VPRICE3	Input Data (E)	Price of each considered EV technology in 1990$	1990 $	TALT3	66
VRANGE1	Input Data (E)	Vehicle range of the considered technology	Miles	TALT1	74
VRANGE2	Input Data (E)	Vehicle range of the considered AFV technology	Miles	TALT2	70
VRANGE3	Input Data (E)	Vehicle range of the considered EV technology	Miles	TALT3	66

LIGHT DUTY VEHICLE STOCK MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
ADJVMTPC	Variable	Demographically-adjusted per capita VMT	Vehicle-miles	TVMT	142
AMPGC	Variable	The average MPG of cars within the reduced AFV size class	Miles per gallon	TMPGSTK	129
AMPGT	Variable	The average MPG of trucks within the reduced AFV size class	Miles per gallon	TMPGSTK	129
ANCMPG	Variable	Average new car MPG	Miles per gallon	TMPGSTK	133
ANTMPG	Variable	Average new light truck MPG	Miles per gallon	TMPGSTK	133
APSHRNC	Variable	Absolute market share of new cars, by technology, from the AFV model	Percent	TMPGSTK	133
APSHRNT	Variable	Absolute market share of new light trucks, by technology, from the AFV model	Percent	TMPGSTK	133
ASC	Index	The three AFV size classes, onto which the six primary size classes are mapped	–		–
CCMPGLDV	Variable	New car MPG, by technology *IT*	MPG	TMPGAG	156
CMPGSTK	Variable	Automobile stock MPG, by vintage and technology	Miles per gallon	TMPGSTK	135
CMPGT	Variable	Automobile stock MPG	Miles per gallon	TMPGSTK	135
COSTMI	Variable	Cost of driving per mile	$ per mile	TVMT	139
DAF	Input Data (C)	Demographic adjustment factor	–	TVMT	142
FLTECHSAL	Variable	Fleet sales by size, technology, and fleet type	Units	TMPGAG	153
FLTECHSALT	Variable	Vehicle purchases by fleet type and technolgy	Units	TMPGAG	153
FLTECHSTK	Variable	Total fleet vehicle stock, by technology and fleet type	Units	TMPGAG	155
FLTMPG	Variable	Fleet vehicle MPG by vehicle type, size class, and technology	MPG	TMPGAG	154
FLTMPGNEW	Variable	New fleet vehicle MPG, by vehicle type and technology *ITECH*	MPG	TMPGAG	156
FLTSTOCK	Variable	New fleet stock, by vehicle type and technology *ITECH*	Units	TMPGAG	155
FLTVMT	Variable	Fleet VMT	Vehicle-miles	TVMT	144
FLVMTSHR	Variable	VMT-weighted shares by size class and technology	Percent	TFREISMOD	148
FVMTSC	Variable	Freight VMT by size class	Vehicle-miles	TVMT	144
INCOME	Variable	Per capita disposable personal income	$	TVMT	140
IS	Index	Index of size class (1-3)	–	TMPGAG	–

LIGHT DUTY VEHICLE STOCK MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
IT	Index	Index of vehicle technology (1-16)	–	TMPGAG	–
IT2	Index	Reassigned indices of vehicle technology *IT2* = 1-16; *IT* = 16,15,1-14	–	TMPGAG	–
ITECH	Index	Index of fleet vehicle technologies which correspond to the *IT* index	–	TMPGAG	–
ITY	Index	Index of fleet type: Business, Government, Utility	–	TMPGAG	–
LTSTK	Variable	Surviving light truck stock, by technology and vintage	Units	TSMOD	120
LVMT	Variable	Average light truck VMT, by vintage, from RTECS	Vehicle miles traveled	TEXOG	134
MPGC	Variable	New car fuel efficiency, by engine technology	Miles per gallon	TMPGSTK	131
MPGC	Variable	New car MPG, by technology *IT*	MPG	TMPGAG	156
MPGFLT	Variable	Stock MPG for all light duty vehicles	Miles per gallon	TMPGSTK	137
MPGT	Variable	New light truck fuel efficiency, by engine technology	Miles per gallon	TMPGSTK	131
MPGTECH	Variable	Average stock MPG by technology	MPG	TMPGSTK	138
NCMPG	Variable	New car MPG, from the FEM model	Miles per gallon	TMPGSTK	132
NCS3A	Variable	New car sales by reduced size class and engine technology: *IS* = 1, *OSC* = 1,6; *IS* = 2, *OSC* = 2,3; *IS* = 3, *OSC* = 4,5	Units	TMPGSTK	125
NCS3SC	Variable	Total new car sales by reduced size class	Units	TMPGSTK	127
NCSR	Variable	Regional new car sales by reduced size class	Units	TMPGSTK	126
NCSTECH	Variable	New car sales, by region, size class, and technology, from the AFV Module	Units	TSMOD	119
NLT3A	Variable	New light truck sales by reduced size class and technolgy: *IS* = 1, *OSC* = 1,3; *IS* = 2, *OSC* = 2,5; *IS* = 3, *OSC* = 4,6	Units	TMPGSTK	125
NLTECH	Variable	New light truck sales, by region, size class, and technology	Units	TSMOD	119
NLTMPG	Variable	New light truck MPG, from the FEM model	Miles per gallon	TMPGSTK	132
NLTS3SC	Variable	Total new light truck sales by reduced size class	Units	TMPGSTK	127
NLTSR	Variable	Regional new light truck sales by reduced size class	Units	TMPGSTK	126
NNCSCA	Variable	New conventional car sales by six size classes	Units	TMPGSTK	128

LIGHT DUTY VEHICLE STOCK MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
NNLTCA	Variable	New conventional light truck sales by six size classes	Units	TMPGSTK	128
OLDFSTK	Variable	Number of fleet vehicles rolled over into corresponding private categories	Units	TSMOD	122
PASSTK	Variable	Surviving automobile stock, by technology and vintage	Units	TSMOD	120
PrFem	Data Input (C)	The ratio of per capita female driving to per capita male driving.	–	TVMT	141
PVMT	Variable	Average automobile VMT, by vintage, from RTECS	Vehicle miles traveled	TEXOG	134
RATIO	Variable	Light truck MPG adjustment factor	–	TMPGSTK	130
RHO	Parameter (C)	Difference equation lag factor, estimated, using the Cochrane-Orcutt iterative procedure, to be 0.72	–	TVMT	141
SCMPG	Variable	Stock MPG for automibles	Miles per gallon	TMPGSTK	136
SSURVLT	Input Data (B)	Fraction of a given vintage's light trucks which survive	Percent	TSMOD	120
SSURVP	Input Data (B)	Fraction of a given vintage's automobiles which survive	Percent	TSMOD	120
STKCAR	Variable	Total stock of non-fleet automobiles in year *T*	Units	TSMOD	123
STKCT	Variable	Stock of non-fleet vehicles, by technology	Units	TMPGAG	158
STKTR	Variable	Total stock of non-fleet light trucks in year *T*	Units	TSMOD	123
STMPG	Variable	Stock MPG for light trucks	Miles per gallon	TMPGSTK	136
STOCKLDV	Variable	Total stock of fleet and non-fleet vehicles, by technology	Units	TMPGAG	158
TECHNCS	Variable	Non-fleet new car sales, by technology *IT*	Units	TMPGAG	156
TECHNCS	Variable	Total new car sales, by technology	Units	TSMOD	119
TECHNLT	Variable	Total new light truck sales, by technology	Units	TSMOD	119
TECHNLT	Variable	Non-fleet new light truck sales, by technology *IT*	Units	TMPGAG	157
TLDVMPG	Variable	Average fuel economy of light-duty vehicles	MPG	TMPGAG	161
TMC_POPAFO	Variable	Total population, from MACRO module	Units	TVMT	140
TMC_SQDTRUCKSL	Variable	Total light truck sales, from MACRO module	Units	TFREISMOD	147
TMC_YD	Variable	Total disposable personal income, from MACRO module	$	TVMT	140
TMPGLDVSTK	Variable	Average MPG by vehicle type *VT*	MPG	TMPGAG	160

LIGHT DUTY VEHICLE STOCK MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
TMPGT	Variable	Light truck stock MPG	Miles per gallon	TMPGSTK	135
TOTMICT	Variable	Total miles driven by cars	Miles	TMPGSTK	134
TOTMITT	Variable	Total miles driven by light trucks	Miles	TMPGSTK	134
TPMGTR	Variable	Price of motor gasoline	$ per gallon	TVMT	139
TRFLTMPG	Variable	Average light truck MPG	MPG	TFREISMOD	152
TRSAL	Variable	Light truck sales for freight	Units	TFREISMOD	147
TRSALTECH	Variable	Light truck sales by technology	Units	TFREISMOD	148
TRSTK	Variable	Total light truck stock	Units	TFREISMOD	151
TRSTKTECH	Variable	Light truck stock by technology	Units	TFREISMOD	149
TRSTKTOT	Variable	Total light truck stock by technology	Units	TFREISMOD	150
TSTOCKLDV	Variable	Total stock by vehicle type *VT*	Units	TMPGAG	159
TTMPGLDV	Variable	New light truck MPG, by technology *IT*	MPG	TMPGAG	157
TTMPGSTK	Variable	Light truck stock MPG, by vintage and technology	Miles per gallon	TMPGSTK	135
VDF	Input Data (N)	Vehicle fuel efficiency degradation factor	Percent	TMPGSTK	135
VMTECH	Variable	Personal travel VMT by technology	Vehicle-miles	TVMT	145
VMTEE	Variable	VMT for personal travel	Vehicle-miles	TVMT	144
VMTLDV	Variable	Total VMT for light duty vehicles	Vehicle-miles	TVMT	143
VSPLDV	Variable	The light duty vehicle shares of each of the sixteen vehicle technologies	Percent	TSMOD	124
VT	Index	Index of vehicle type: 1 = cars, 2 = light trucks	–	TMPGAG	–
XLDVMT	Variable	Fractional change of VMT over base year (1990)	Percent	TVMT	146

LIGHT DUTY VEHICLE FLEET MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
APSHR55	Variable	Absolute regional market shares of adjusted vehicle sales	Percent	TLEGIS	102
APSHRFLTB	Variable	Market shares of business fleet by vehicle type and technology	Percent	TLEGIS	106
APSHRFLTB	Variable	Alternative technology shares for the business fleet	Percent	TLEGIS	84
APSHRFLTOT	Variable	Aggregate market shares of fleet vehicle technologies	Percent	TLEGIS	105
APSHRNC	Variable	Market shares of new cars by technology	Percent	TLEGIS	104
APSHRNT	Variable	Market shares of new light trucks by technology	Percent	TLEGIS	104
AVSALES	Variable	Regional adjusted vehicle sales by size class	Units	TLEGIS	97
AVSALEST	Variable	Total regional adjusted vehicle sales by size class	Units	TLEGIS	100
ELECVSAL	Variable	Regional electric vehicle sales	Units	TLEGIS	92
ELECVSALSC	Variable	Regional ZEV sales within corresponding regions	Units	TLEGIS	96
EPACT	Parameter (H)	Legislative mandates for AFV purchases, by fleet type	Percent	TEXOG	81
FLTALT	Variable	Number of AFV's purchased by each fleet type in a given year	Units	TFLTSTKS	81
FLTAPSHR1	Input Data (G)	Fraction of each fleets' purchases which are AFV's, from historical data	Percent	TEXOG	81
FLTCONV	Variable	Fleet purchases of conventional vehicles	Units	TFLTSTKS	82
FLTCRAT	Input Data (G)	Fraction of total car sales attributed to fleets	Percent	TEXOG	80
FLTCSHR	Input Data (G)	Fraction of fleet cars purchased by a given fleet type	Percent	TEXOG	80
FLTECH	Variable	Vehicle purchases by fleet type and technology	Units	TFLTSTKS	85
FLTECHSAL	Variable	Fleet sales by size, technology, and fleet type	unts	TFLTSTKS	84
FLTECHSHR	Input Data (G)	Alternative technology shares for the government and utility fleets	Percent	TEXOG	84
FLTFCLDVBTU	Variable	Fuel consumption by vehicle type and technology	MMBtu	TFLTCONS	117
FLTFCLDVBTUR	Variable	Regional fuel consumption by fleet vehicles, by technology	MMBtu	TFLTCONS	118

LIGHT DUTY VEHICLE FLEET MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
FLTLDVC	Variable	Fuel consumption by technology, vehicle and fleet type	MMBtu	TFLTCONS	116
FLTMPG	Variable	New fleet vehicle fuel efficiency, by fleet type and engine technology	Miles per Gallon	TFLTMPG	110
FLTMPGTOT	Variable	Overall fuel efficiency of new fleet cars and light trucks	MPG	TFLTMPG	112
FLTSAL	Variable	Sales to fleets by vehicle and fleet type	Units	TFLTSTKS	80
FLTSLSCA	Variable	Fleet purchases of AFV's, by size class	Units	TFLTSTKS	83
FLTSLSCC	Variable	Fleet purchases of conventional vehicles, by size class	Units	TFLTSTKS	83
FLTSSHR	Input Data (G)	Percentage of fleet vehicles in each size class, from historical data	Percent	TEXOG	83
FLTSTKVN	Variable	Fleet stock by fleet type, technology, and vintage	Units	TFLTSTKS	86
FLTTOTMPG	Variable	Fleet vehicle average fuel efficiency for cars and light trucks	Miles per Gallon	TFLTMPG	115
FLTTRAT	Input Data (G)	Fraction of total truck sales attributed to fleets	Percent	TEXOG	80
FLTTSHR	Input Data (G)	Fraction of fleet trucks purchased by a given fleet type	Percent	TEXOG	80
FLTVMT	Variable	Total VMT driven by fleet vehicles	Vehicle Miles Traveled	TFLTVMTS	108
FLTVMTECH	Variable	Fleet VMT by technology, vehicle type, and fleet type	Vehicle Miles Traveled	TFLTVMTS	109
FLTVMTYR	Variable	Annual miles of travel per vehicle, by vehicle and fleet type	Miles	TFLTVMTS	108
FMSHC	Variable	The market share of fleet cars, from the AFV model	Percent	TFLTMPG	110
FMSHLT	Variable	The market share of fleet light trucks, from the AFV model	Percent	TFLTMPG	110
IR	Index	Corresponding regions: *ST* = CA, MA, NY; *IR* = 9,1,2	—	TLEGIS	—
IS	Index	Index of size classes: 1 = small, 2 = medium, 3 = large	—	TFLTSTKS	—
ITECH	Index	Index of engine technologies: 1-5 = alternative fuels (neat), 6 = gasoline	—	TFLTSTKS	—
ITF	Index	Index of fleet vehicle technologies, corresponding to *IT* = 3,5,7,8,9	—	TLEGIS	—
ITY	Index	Index of fleet type: 1 = business, 2 = government, 3 = utility	—	TFLTVMTS	—
MAXVINT	Index	Maximum *IVINT* index associated with a given vehicle and fleet type	—	TFLTMPG	—

LIGHT DUTY VEHICLE FLEET MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
MPGFLTSTK	Variable	Fleet MPG by vehicle and fleet type, and technology, across vintages	Miles per Gallon	TFLTMPG	114
MPGFSTK	Variable	Fleet MPG by vehicle and fleet type, technology, and vintage	Miles per Gallon	TFLTMPG	113
NAMPG	Variable	New AFV fuel efficiency, from the AFV model	Miles per Gallon	TALT3	110
NCSTECH	Variable	Regional new car sales by technology, within six size classes: *OSC* = 1-6; *IS* = 2,1,1,3,3,2	Units	TLEGIS	107
NLTECH	Variable	Regional light truck sales by technology, with six size classes: *OSC* = 1-6; *IS* = 1,2,1,3,2,3	Units	TLEGIS	107
OLDFSTK	Variable	Old fleet stocks of given types and vintages, transferred to the private sector	Units	TFLTSTKS	87
QBTU	Input Data (I)	Energy content of the fuel associated with each technology	Btu/Gal	TFLTCONS	117
RSHR	Variable	Regional VMT shares, from the Regional Sales Module	Percent	TREG	118
ST	Index	Index of participating state: CA, MA, NY	—	TLEGIS	—
STATESHR	Variable	Share of national vehicle sales attributed to a given state	Percent	TLEGIS	94
SURVFLTT	Input Data (G)	Survival rate of a given vintage	Percent	TFLTSTKS	86
TFLTECHSTK	Variable	Total stock within each technology and fleet type	Units	TFLTSTKS	88
TMC_SQDTRUCKSL	Variable	Total light truck sales in a given year	Units	TMAC	80
TMC_SQTRCARS	Variable	Total automobile sales in a given year	Units	TMAC	80
TOTFLTSTK	Variable	Total of all surviving fleet vehicles	Units	TFLTSTKS	89
ULEV	Data Input (J)	State-mandated minimum sales share of ULEV's	Percent	TLEGIS	94
ULEVST	Variable	State-mandated minimum sales of ULEV's	Units	TLEGIS	94
VFSTKPF	Variable	Share of fleet stock by vehicle type and technology	Percent	TFLTSTKS	90
VSALES	Variable	Total disaggregate vehicle sales	Units	TLEGIS	91
VSALESC16	Variable	Total new car sales by technology: *IS* = 1, *OSC* = 2,3; *IS* = 2, *OSC* = 1,6; *IS* = 3, *OSC* = 4,5	Units	TLEGIS	103
VSALEST	Variable	Total regional vehicle sales, by size class	Units	TLEGIS	93
VSALEST16	Variable	Total new light truck sales by technology: *IS* = 1, *OSC* = 1,3; *IS* = 2, *OSC* = 2,5; *IS* = 3, *OSC* = 4,6	Units	TLEGIS	103
VT	Index	Index of vehicle type: 1 = cars, 2 = light trucks	—	TFLTSTKS	—

LIGHT DUTY VEHICLE FLEET MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
ZEV	Data Input (J)	State-mandated minimum sales share of ZEV's	Percent	TLEGIS	94
ZEVST	Variable	State-mandated minimum sales of ZEV's	Units	TLEGIS	94
ZEVSTSC	Variable	Mandated ZEV sales by size class and state	Units	TLEGIS	95

AIR TRAVEL MODULE: Air Travel Demand Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
DFRT	Parameter (O)	Fraction of freight ton-miles transported on dedicated carriers.	Percent	TAIRT	199
DI	Parameter (O)	Demographic air travel index, reflecting public's propensity to fly	–	TAIRT	201
EQSM	Input Data (O)	Equivalent seat-miles conversion factor; used to transform freight RTMs to seat-miles	–	TAIRT	204
LFDOM	Parameter (O)	Load factor, the average fraction of seats which are occupied in domestic travel.	Percent	TAIRT	204
LFINTER	Parameter (O)	Load factor for international travel.	Percent	TAIRT	204
OPCST	Input Data (O)	Airline operating costs.	Dollars per Aircraft-Mile	TAIRT	195
PCTINT	Parameter (O)	Proportionality factor relating international to domestic travel levels	–	TAIRT	198
RPMB	Variable	Revenue passenger miles of domestic travel for business purposes.	Passenger Miles	TAIRT	200
RPMBPC	Variable	Per capita domestic RPM for business travellers.	Miles per Capita	TAIRT	196
RPMD	Variable	Total domestic revenue passenger miles.	Passenger Miles	TAIRT	203
RPMI	Variable	Revenue passenger miles of international travel.	Passenger Miles	TAIRT	202
RPMIPC	Variable	Per capita international RPM	Miles per Capita	TAIRT	198
RPMP	Variable	Revenue passenger miles of domestic travel for personal purposes.	Passenger Miles	TAIRT	201
RPMPPC	Variable	Per capita domestic RPM for personal travel.	Miles per Capita	TAIRT	197
RTM	Variable	Revenue ton miles of cargo.	Ton Miles	TAIRT	199
ASMDEMD	Variable	Total seat-miles demanded for domestic and international travel	Seat Miles	TAIRT	204

AIR TRAVEL MODULE: Air Travel Demand Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
TMC_GDP	Variable	Real gross domestic product	Dollars per Capita	TMAC	196
TMC_POPAFO	Variable	U.S. population	People	TMAC	196
TMC_YD	Variable	Real gross disposable personal income	Dollars per Capita	TMAC	197
TPJFTR	Variable	Price of Jet Fuel.	Dollars per Gallon	TMAC	195
YIELD	Variable	Airline revenue per passenger mile	Dollars per Passenger-Mile	TAIRT	195

AIR TRAVEL MODULE: Aircraft Fleet Efficiency Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
AGD	Variable	Demand for aviation gasoline, in gallons	Gallons	TAIREFF	226
AGDBTU	Variable	Aviation gasoline demand, in Btu	Btu	TAIREFF	224
AIRHRS	Input Data (P)	Average number of airborne hours per aircraft, by type.	Hours per Year	TAIREFF	205
ASMDEMD	Variable	Demand for available seat-miles, by aircraft type	Seat Miles	TAIREFF	207
ASMP	Variable	The available seat-miles per plane, by type	Seat Miles	TAIREFF	205
AVSPD	Input Data (P)	Average flight speed, by type.	Miles per Hour	TAIREFF	205
BASEAGD	Parameter	Baseline demand for aviation gasoline	Gallons	TAIREFF	223
BASECONST	Parameter	Baseline constant, used to anchor the technology penetration curve	–	TAIREFF	216
COSTFX	Parameter	Factor reflecting the magnitude of the difference between the price of jet fuel and the trigger price of the considered technology	–	TAIREFF	215
DELTA	Parameter	User-specified rate of passenger shifts between aircraft types	–	TAIREFF	206
EFFIMP	Input Data (P)	Fractional improvement associated with a given technology	Percent	TAIREFF	218
FRACIMP	Variable	Fractional improvement over base year (1990) fuel efficiency, by type	Percent	TAIREFF	218
GAMMA	Parameter (P)	Baseline adjustment factor	–	TAIREFF	223
IFX	Index	Index of technology improvements (1-6)	–	TAIREFF	–

AIR TRAVEL MODULE: Aircraft Fleet Efficiency Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
IT	Index	Index of aircraft type: 1 = narrow body, 2 = wide body	–	TAIREFF	–
IVINT	Index	Index of aircraft vintage	–	TAIREFF	–
IYEAR	Index	Current year	–	TAIREFF	–
JFBTU	Variable	Jet fuel demand, in Btu	Btu	TAIREFF	224
JFGAL	Variable	Consumption of jet fuel, in gallons	Gallons	TAIREFF	222
KAPPA	Parameter (P)	Exogenously-specified decay constant	–	TAIREFF	223
NEWSMPG	Variable	Average seat-miles per gallon of new aircraft purchases	SMPG	TAIREFF	219
NPCHSE	Variable	Number of aircraft purchased, by body type.	Aircraft	TAIREFF	209
NSURV	Variable	Number of surviving aircraft, by body type.	Aircraft	TAIREFF	212
QAGR	Variable	Regional demand for aviation gasoline	Btu	TAIREFF	225
QJETR	Variable	Regional demand for jet fuel	Btu	TAIREFF	225
RHO	Parameter (P)	Average historic rate of growth of fuel efficiency	–	TAIREFF	220
SEAT	Input Data (P)	Average number of seats per aircraft, by type.	Seats per Aircraft	TAIREFF	205
SMFRACN	Variable	Fraction of seat-mile demand on narrow-body planes	Percent	TAIREFF	206
SMFRACN	Variable	Fraction of seat miles handled by surviving stock and new purchases, by type.	—	TAIREFF	221
SMPG	Variable	Average seat miles per gallon for new purchases and surviving fleet, by type.	Seat Miles per Gallon	TAIREFF	219
SMPGT	Variable	Overall fleet average seat-miles per gallon	SMPG	TAIREFF	221
SMSURV	Variable	Surviving travel capacity by body type.	Seat Miles	TAIREFF	209
SSURVPCT	Parameter (P)	Marginal survival rate of planes of a given vintage	Percent	TAIREFF	208
STKOLD	Variable	Fraction of planes older than one year, by aircraft type	Percent	TAIREFF	213
SURVK	Parameter (P)	User-specified proportionality constant	–	TAIREFF	208
SURVPCT	Input Data (P)	Survival rate of planes of a given vintage *IVINT*	Percent	TAIREFF	208
TS0	Parameter (P)	User-specified vintage at which stock survival is 50%	Years	TAIREFF	208
TIMECONST	Parameter (P)	User-specified scaling constant, reflecting the importance of the passage of time	–	TAIREFF	214

AIR TRAVEL MODULE: Aircraft Fleet Efficiency Model					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
TIMEFX	Parameter (P)	Factor reflecting the length of time an aircraft technology improvement has been commercially viable	–	TAIREFF	214
TOTALFX	Parameter (P)	Overall effect of fuel price and time on implementation of technology *IFX*	–	TAIREFF	216
TPJFGAL	Variable	Price of jet fuel	$ per Gallon	TAIREFF	215
TPN	Variable	Binary variable (0,1) which tests whether current fuel price exceeds the considered techology's trigger price	–	TAIREFF	214
TPZ	Variable	Binary variable which tests whether implementation of the considered technology is dependent on fuel price	–	TAIREFF	215
TRIGPRICE	Parameter (P)	Price of jet fuel above which the considered technology is assumed to be commercially viable	$ per Gallon	TAIREFF	215
TYRN	Variable	Binary variable which tests whether current year exceeds the considered technology's year of introduction	–	TAIREFF	215
XAIR	Variable	Fractional change in air travel from base year	Percent	TAIREFF	226
XAIREFF	Variable	Fractional change in aircraft fuel efficiency from base year	Percent	TAIREFF	226

FREIGHT TRANSPORT MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
FAC	Input Data (Q)	Freight Adjustment Coefficient—relates growth in value added in industry I to growth in freight transportation	–	TFREI	162
FBENCH	Parameter (I)	Benchmarking factor to ensure congruence with 1990 data	–	TFREI	168
FERAIL	Input Data (B)	Rail fuel efficiency	Miles per gallon	TRAIL	182
FESHIP	Input Data (B)	Domestic freighter fuel efficiency		TSHIP	188
FFD	Variable	Truck Fuel Demand, by type of fuel and class of vehicle.	MMBtu	TFREI	176
FFDT	Variable	Total fuel demand, by technology, in MMBtu	Gallons	TFREI	178
FFMPG	Variable	Average truck fuel economy for second size class for use in TMISC	MPG	TFREI	177
FFVMT	Variable	Total freight truck vehicle-miles traveled in industry group *IX*	Vehicle-miles	TFREI	165

FREIGHT TRANSPORT MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
FLVMTSHR	Variable	Share of fuel technology in total truck VMT	Percent	TFREI	169
FMPG	Variable	Truck Fuel Efficiency, by class of truck.	Miles per Gallon	TFREI	174
FRLOAD	Parameter (Q)	Load factor associated with a given industry's output	–	TFREI	163
FSHR	Variable	Adjusted technology share of VMT demand	Percent	TFREI	169
FTMT	Variable	Total highway freight traffic, by industry	Ton Miles	TFREI	162
FTOTVMT	Variable	Total VMT demand for trucks	Vehicle miles	TFREI	166
FVMT	Variable	Freight transport demand by class of truck.	Vehicle Miles	TFREI	163
FVMTECHSC	Variable	Total highway freight VMT, by size class and fuel technology	Vehicle Miles	TFREI	172
FVMTSC	Variable	Total highway freight VMT, by size class	Vehicle Miles	TFREI	168
GROSST	Variable	Value of gross trade (imports + exports)	$	TSHIP	191
GROWTH	Parameter	Factor which specifies changes in truck VMT by each fuel technology over time	–	TFREI	169
IF	Index	Index of fuel type	–	TRAIL	–
IS	Index	Index of truck size class (1-3)	–	TFREI	–
ISFD	Variable	International freighter energy demand, by fuel	MMBtu	TSHIP	192
ISFDT	Variable	Total international shipping energy demand	MMBtu	TSHIP	191
ISFSHARE	Parameter (B)	International shipping fuel allocation factor	–	TSHIP	192
IX	Index	Place holder for industry group	–	TFREI	–
OUTPUT	Variable	Value of output of each industry in base year dollars.	Dollars	TFREI	162
QBTU	Input Data (I)	Heat content of fuel used by each technology	MMBtu per gallon	TFREI	176
RTMT	Variable	Total rail freight traffic, by industry	Ton Miles	TRAIL	180
RTMTT	Variable	Total rail ton-miles traveled	Ton Miles	TRAIL	181
SEDSHR	Parameter (K)	Regional shares of shipping fuel demand	Percent	TFREI	179
SFD	Variable	Domestic freighter energy demand, by fuel	MMBtu	TSHIP	189
SFDBENCH	Parameter (I)	Benchmark factor to ensure congruence with 1990 data	–	TSHIP	188

FREIGHT TRANSPORT MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
SFDT	Variable	Domestic freighter energy demand	MMBtu	TSHIP	188
SFSHARE	Parameter (B)	Domestic shipping fuel allocation factor	–	TSHIP	189
STMT	Variable	Total waterborne freight traffic, by industry	Ton Miles	TSHIP	186
STMTT	Variable	Total ship ton-miles traveled	Ton Miles	TSHIP	187
SUMFVMT	Variable	Total freight VMT for the second size class for use in TMISC	Vehicle Miles	TFREI	173
TBETA1	Parameter	Base rate of fuel economy growth, by size class	Percent	TFREI	174
TBETA2	Parameter	Fuel-price sensitive rate of fuel economy growth, by size class	Percent	TFREI	174
TECH	Index	Index of engine technology (1-5)	–	TFREI	–
TMC_YD	Variable	Disposable personal income, from the MACRO module	$	TFREI	165
TPMGTR	Variable	Price of motor gasoline used for highway transport	$ per Gallon	TFREI	174
TQFREIR	Variable	Total regional truck fuel consumption for each technology	MMBtu	TFREI	179
TQFREIRSC	Variable	Total regional freight energy demand by technology and size class	MMBtu	TFREI	179
TQISHIPR	Variable	Total regional energy demand by international freighters	MMBtu	TSHIP	193
TQRAIL	Variable	Total demand for each fuel by rail freight sector in year *T*	MMBtu	TRAIL	183
TQRAILR	Variable	Total regional rail fuel consumption for each technology	MMBtu	TRAIL	184
TQRAILT	Variable	Total energy consumption by freight trains in year *T*	MMBtu	TRAIL	182
TQSHIPR	Variable	Total regional energy demand by domestic freighters, by fuel type	MMBtu	TSHIP	190
TRSCSHR	Input Data (B)	Travel share distribution factors, held constant	–	TFREI	168
TSIC	Variable	Value of output of industry *I*, in base year (1990) dollars	$	TFREI	162
TSIC90	Input Data (I)	Base year value of industrial output	$	TFREI	165
TYD8290	Input Data (I)	Base year disposable personal income	$	TFREI	165
XFREFF	Variable	Fuel economy improvement over base year	Percent	TFREI	175
XRAIL	Variable	Growth in rail travel from base year	Percent	TRAIL	185

FREIGHT TRANSPORT MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
XRAILEFF	Variable	Growth in rail efficiency from base year	Percent	TRAIL	185
XSHIP	Variable	Growth in ship travel from base year	Percent	TSHIP	194
XSHIPEFF	Variable	Growth in ship efficiency from base year	Percent	TSHIP	194
XTOTVMT	Variable	Fractional growth in freight VMT over base year	Percent	TFREI	167

MISCELLANEOUS ENERGY DEMAND MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
BETALUB	Parameter (K)	Coefficient of proportionality, relating highway travel to lubricant demand	–	TMISC	238
BETAMS	Parameter (B)	Coefficient of proportionality, relating mass transit to LDV travel	–	TMISC	230
BETAREC	Parameter (B)	Coefficient of proportionality relating income to fuel demand for boats	–	TMISC	234
FLTVMT	Variable	Total fleet vehicle VMT, from the Fleet Module	Vehicle Miles	TFLTVMTS	237
FMPG	Variable	Fuel efficiency for mass transit vehicles, by vehicle type, from the Freight Module	Miles per gallon	TFREI	231
FMPG89	Data Input (B)	Base-year fuel efficiency for mass transit vehicles, by vehicle type, from the Freight Module	Miles per gallon	TEXOG	231
FTVMT	Variable	Total freight truck VMT, from the Freight Module	Vehicle Miles	TMISC	236
FVMTSC	Variable	Freight truck VMT, by size class		TMISC	236
HYWAY	Variable	Total highway VMT	Vehicle Miles	TMISC	237
IF	Index	Index of fuel type: 1=Distillate, 2=Naphtha, 3=Residual, 4=Kerosene	–	TMISC	–
IM	Index	Index of transportation mode: 1 = LDV's, 2-4 = Buses, 5-7 = Rail	–	TMISC	–
IM	Index	Index of transportation mode: 1 = LDV's, 2-4 = Buses, 5-7 = Rail		TMISC	–
LUBFD	Variable	Total demand for lubricants in year T	MMBtu	TMISC	238
MFD	Variable	Total military consumption of each fuel in year T	MMBtu	TMISC	228
MILTARGR	Variable	The growth in the military budget from the previous year	Percent	TMISC	227
MILTRSHR	Input Data (L)	Regional consumption shares, from 1991 data, held constant	Percent	TMISC	229
QLUBR	Variable	Regional demand for lubricants in year T	MMBtu	TMISC	239
QMILTR	Variable	Regional military fuel consumption, by fuel type	MMBtu	TMISC	229
QMODR	Variable	Regional consumption of fuel, by mode	MMBtu	TMISC	233
QRECR	Variable	Regional fuel consumption by recreational boats in year T	MMBtu	TMISC	235
RECFD	Variable	National recreational boat gasoline consumption in year T	MMBtu	TMISC	234
TMC_GFML87	Variable	Total defense budget in year T, from the macro economic segment of NEMS	$	TMAC	227

MISCELLANEOUS ENERGY DEMAND MODULE					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
TMC_POPAFO	Variable	Regional population forecasts, from the Macro Module	People	TMAC	233
TMC_YD	Variable	Total disposable personal income, from the Macro Module	$	TMAC	234
TMEFF89	Input Data (B)	Base-year Btu per vehicle-mile, by mass transit mode	Btu per vehicle mile	TMISC	231
TMEFFL	Variable	Btu per passenger-mile, by mass transit mode	Btu per passenger mile	TMISC	231
TMFD	Variable	Total mass-transit fuel consumption by mode	Gallons	TMISC	232
TMOD	Variable	Passenger-miles traveled, by mode	Passenger miles	TMISC	230
TMLOAD89	Data Input (B)	Average passengers per vehicle, by mode, held constant at 1989 values (1=LDV's)	Units	TMISC	230
TYPE	Index	Vehicle type, from the Freight Module: 1 = Mid-size trucks, 2 = Rail	–	TFREI	231
VMTEE	Variable	LDV vehicle-miles traveled, from the VMT module	Vehicle miles	TVMT	230

Transportation Emissions Module					
ITEM	CLASS.	DESCRIPTION	UNITS	SUBROUTINE	EQ #
EFACT	Parameter (M)	Emissions factor relating measures of travel to pollutant emissions	–	TEMISS	240
EMISS	Variable	Regional emissions of a given pollutant, by mode of travel	Tons per year	TEMISS	240
IE	Index	Index of pollutants: 1 = SO_x, 2 = NO_x, 3 = C, 4 = CO_2, 5 = CO, 6 = VOC	–	TEMISS	240
IM	Index	Index of travel mode: references individual vehicle types used in the preceding modules	–	TEMISS	240
IR	Index	Index identifying census region	–	TEMISS	240
U	Variable	Measure of travel demand, by mode: units in VMT for highway travel, gallons of fuel consumption for other modes	–	TEMISS	240

SOURCES OF DATA INPUTS AND PARAMETERS USED IN THE NEMS TRANSPORTATION MODEL

CODE	SOURCE
A	*Conventional Light-Duty Vehicle Fuel Economy*, Decision Analysis Corporation of Virginia and Energy and Environmental Analysis, Inc., Prepared For: Energy Information Administration, U.S. Department of Energy, Washington D.C., November, 1992.
B	*Transportation Energy Data Book: Edition 12*, Oak Ridge National Laboratory, Prepared For: Office of Transportation Technologies, U.S. Department of Energy, Washington, D.C., March 1992.
C	*Revised VMT Forecasting Model*, Unpublished Memorandum, U.S. Department of Energy, February 22, 1993.
D	*1990 National Personal Transportation Survey*, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., March 1992.
E	*Alternative-Fuel Vehicle Module*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., September 1992.
F	*Demand for Clean-Fuel Personal Vehicles in California: A Discrete-Choice Stated Preference Survey*, D. S. Bunch, *et. al.*, University of California, Davis, UCD-ITS-RR-91-14, December 1991.
G	*Fleet Vehicles in the United States*, Oak Ridge National Laboratories, Prepared For: Office of Transportation Technologies and Office of Policy, Planning and Analysis, U.S. Department of Energy, Washington, D.C., March 1992.
H	*Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector; Technical Report Ten: Analysis of Alternative-Fuel Fleet Requirements*, Office of Domestic and International Energy Policy, U.S. Department of Energy, May 1992.
I	*Annual Energy Outlook 1993*, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, D.C., January 1993.
J	*Proposed Regulations for Low-Emission Vehicles and Clean Fuels*, State of California Air Resources Board, August 13, 1990.
K	*State Energy Data Survey 1991*, Energy Information Administration, Office of Energy Markets and End Use, U.S. Department of Energy, Washington, D.C., May 1993.
L	*Fuel Oil and Kerosene Sales 1991*, Energy Information Administration, Office of Oil and Gas, U.S. Department of Energy, Washington D.C., November 1992.
M	*Emissions Regulations, Inventories, and Emission Factor for the NEMS Transportation Energy and Research Forecasting Model*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., September 1992.
N	*Fuel Efficiency Degradation Factor*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., August 1992.
O	*Proposed Methodology for Projecting Air Transportation Demand*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., July 1992.
P	*Preliminary Estimation of the NEMS Aircraft Fleet Efficiency Module*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., September 1992.
Q	*Freight Transportation Requirements Analysis for the NEMS Transportation Sector Model*, Decision Analysis Corporation of Virginia, Prepared For: Energy Information Administration, U.S. Department of Energy, Washington, D.C., August 1992.

Table A-2. Light Duty Vehicle Market Classes

CLASS	DEFINITION	EXAMPLE MODEL
AUTOMOBILES (Domestic and Import)		
Minicompact	Interior passenger volume < 79 ft^3	Geo Metro, Toyota Paseo (no domestic cars)
Subcompact	Passenger volume between 79 ft^3 and 89 ft^3	Nissan Sentra, Honda Civic, GM Saturn, Ford Escort
Sports	Two door high performance cars costing less than $25,000	VW Corrado, Honda Prelude, Chevy Camaro, Ford Mustang
Compact	Passenger volume between 89 and 95 ft^3	Honda Accord, Toyota Camry, Ford Tempo, Pontiac Grand Am
Intermediate	Passenger volume between 96 and 105 ft^3	Nissan Maxima, Ford Taurus, Chevy Lumina
Large	Passenger volume >105 ft^3	Ford Crown Victoria, Pontiac Bonneville (no imports)
Luxury	Cars over $25,000	Lincoln Continental, Cadillac, all Mercedes, Lexus LS400
LIGHT TRUCKS (Domestic and Import)		
Compact Pickup	Trucks with inertia weight between 2750 and 4000 lbs.	All import trucks, Ford Ranger, GM S-10/15
Compact Van	Vans with inertia weight between 3000 and 4250 lbs.	All import vans, Plymouth, Voyager, Ford Aerostar
Compact Utility	Utility vehicles with inertia weight between 3000 and 4250 lbs.	Nissan Pathfinder, Toyota SR-5, Ford Bronco II, Jeep Cherokee
Standard Pickup	Trucks with inertia weight over 4000 lbs.	GM C-10, Ford F-150 (no imports)
Standard Van	Vans with inertia weight over 4250 lbs.	GM C15 van, Ford E-150 (no imports)
Standard Utility	Utility vehicles with inertia weight over 4250 lbs.	Toyota Land Cruiser, GM Suburban, Ford Blazer
Mini-truck	Utility/trucks below 2750 lbs. inertia weight	Suzuki Samurai (no domestics)

Table A-3. Maximum Light Duty Vehicle Market Penetration Parameters

Old Market Share	New PMAX (Automobiles)	New PMAX (Light Trucks)
≤ 1%	1%	1%
1.1-2%	2%	2%
2.1-3%	5%	5%
3.1-6%	12%	10%
6.1-10%	28%	22%
10.1-12%	32%	26%
12.1-14%	36%	30%
14.1-17%	41%	35%
17.1-20%	47%	40%
20.1-24%	53%	47%
24.1-27%	56%	50%
27.1-31%	60%	54%
31.1-35%	64%	58%
35.1-40%	68%	62%
40.1-45%	73%	67%
45.1-53%	78%	73%
53.1-62%	83%	79%
62.1-73%	88%	85%
73.1-85%	94%	92%
85.1-100%	100%	100%

Table A-4. Aircraft Fleet Efficiency Model Adjustment Factors

Year	DI	PCTINT	DFRT
1979	0.974	0.27	0.509
1980	0.976	0.32	0.523
1981	0.978	0.30	0.514
1982	0.980	0.28	0.509
1983	0.982	0.27	0.508
1984	0.985	0.28	0.522
1985	0.988	0.28	0.518
1986	0.991	0.25	0.520
1987	0.994	0.28	0.540
1988	0.996	0.30	0.545
1989	0.998	0.33	0.551
1990	1.000	0.35	0.555
1991	1.003	0.38	0.564
1992	1.004	0.40	0.569
1993	1.005	0.41	0.573
1994	1.007	0.42	0.577
1995	1.008	0.43	0.579
1996	1.007	0.44	0.584
1997	1.007	0.45	0.585
1998	1.006	0.46	0.591
1999	1.006	0.46	0.593
2000	1.005	0.47	0.598
2001	1.003	0.47	0.601
2002	1.001	0.48	0.604
2003	0.998	0.48	0.604
2004	0.996	0.48	0.604
2005	0.994	0.48	0.604
2006	0.992	0.49	0.604
2007	0.989	0.49	0.604
2008	0.987	0.49	0.604
2009	0.985	0.49	0.604
2010	0.983	0.49	0.604
2011	0.980	0.49	0.604
2012	0.978	0.49	0.604
2013	0.975	0.50	0.604
2014	0.972	0.50	0.604
2015	0.970	0.50	0.604
2016	0.967	0.50	0.604
2017	0.965	0.50	0.604
2018	0.962	0.50	0.604
2019	0.960	0.50	0.604
2020	0.957	0.50	0.604
2021	0.956	0.50	0.604
2022	0.954	0.50	0.604
2023	0.952	0.50	0.604
2024	0.951	0.50	0.604
2025	0.949	0.50	0.604
2026	0.948	0.50	0.604
2027	0.946	0.50	0.604
2028	0.944	0.50	0.604
2029	0.943	0.50	0.604
2030	0.941	0.50	0.604

Table A-5. List of Expected Aircraft Technology Improvements

Proposed Technology	Intro. Year	Jet Fuel Price[1] ('87 $/Gal)	SMPG Gain Over 1990's	
			Narrow Body	Wide Body
ENGINES:				
Ultra-high Bypass	1995	$0.69	10%	10%
Propfan	2000	$1.36	23%	0%
AERODYNAMICS:				
Hybrid Laminar Flow	2020	$1.53	15%	15%
Advanced Aerodynamics	2000	$1.70	18%	18%
OTHER:				
Weight Reducing Materials	2000	–	15%	15%
Thermodynamics	2010	$1.22	20%	20%

[1] These figures represent the minimum jet fuel prices (1987 $) at which the corresponding technologies are assumed to become cost-effective.

Appendix B. Mathematical Representation

TABLE OF CONTENTS

Introduction B-1

LIGHT DUTY VEHICLE MODULE B-2
- FUEL ECONOMY MODEL B-2
  - Subroutine FEMCALC B-2
  - Subroutine NOTESSUPER B-7
  - Subroutine CMKSCALC B-9
  - Subroutine CAFECALC B-10
- REGIONAL SALES MODEL B-10
  - Subroutine FEMSIZE B-10
  - Subroutine TSIZE B-12
  - Subroutine TREG B-15
- ALTERNATIVE FUEL VEHICLE MODEL B-17
  - Subroutine TALT3 . . . . . B-17

LIGHT DUTY VEHICLE FLEET MODULE B-23
- Subroutine TFLTSTKS B-23
- Subroutine TLEGIS B-26
- Subroutine TFLTVMTS B-31
- Subroutine TFLTMPG B-32
- Subroutine TFLTCONS B-34

LIGHT DUTY VEHICLE STOCK MODULE B-35
- LIGHT DUTY VEHICLE STOCK ACCOUNTING MODEL B-35
  - Subroutine TSMOD B-35
  - Subroutine TMPGSTK B-37
- VEHICLE MILES TRAVELED MODEL B-42
  - Subroutine TVMT B-42
  - Subroutine TFREISMOD B-44
  - Subroutine TMPGAG B-46

TABLE OF CONTENTS (CONT.)

FREIGHT TRANSPORT MODULE B-49
HIGHWAY FREIGHT MODEL B-49
Subroutine TFREI B-49
RAIL FREIGHT MODEL B-53
Subroutine TRAIL B-53
WATERBORNE FREIGHT MODEL B-55
Subroutine TSHIP B-55

AIR TRAVEL MODULE B-58
AIR TRAVEL DEMAND MODEL B-58
Subroutine TAIRT B-58
AIRCRAFT FLEET EFFICIENCY MODEL B-60
Subroutine TAIREFF B-60

MISCELLANEOUS TRANSPORTATION ENERGY DEMAND MODULE B-67
MILITARY DEMAND MODEL B-67
Subroutine TMISC B-67
MASS TRANSIT DEMAND MODEL B-68
Subroutine TMISC B-68
RECREATIONAL BOATING DEMAND MODEL B-69
Subroutine TMISC B-69
LUBRICANT DEMAND MODEL B-70
Subroutine TMISC B-70

VEHICLE EMISSIONS MODULE B-71
Subroutine TEMISS B-71

Introduction

This appendix provides a detailed mathematical description of the transportation model. Equations are presented in the order in which they are encountered in the code, identified by subroutine and model component. The equations follow the logic of the FORTRAN source code very closely to facilitate an understanding of the code and its structure. In several instances, a variable name will appear on both sides of an equation. This is a FORTRAN programming device that allows a previous calculation to be updated (for example, multiplied by a factor) and re-stored under the same variable name.

In the interest of clarity, initialization statements, variable name reassignments, and error-trapping tests are omitted, except where such descriptions are essential to an understanding of the process. Representative equations are also employed in those instances where the model specifies numerous, but essentially identical, calculations (most notably in the emissions component).

FUEL ECONOMY MODEL — Subroutine FEMCALC

1) Calculate the fuel cost slope, used to linearly extrapolate expected fuel cost over the desired payback period:

$$PSLOPE = \frac{MAX\ (0, FUELCOST_{YEAR-6} - FUELCOST_{YEAR-8})}{2} \qquad \text{(B-1)}$$

where:

PSLOPE = The fuel cost slope
FUELCOST = The cost of fuel in the specified prior years

2) Calculate the expected fuel price in year i (where i goes from 1 to PAYBACK):

$$PRICE\$EX_i = PSLOPE * (i+2) + FUELCOST_{YEAR-8} \qquad \text{(B-2)}$$

where

$PRICE\$EX_i$ = The expected price of fuel

3) Calculate the expected present value of fuel savings over the payback period:

$$\sum_{i=1}^{PAYBACK} VMT_i * \left(\frac{1}{FE_{itc,YEAR-1}} - \frac{1}{(1 + DEL\$FE_{itc} * FE_{itc,YEAR-1})} \right) * PRICE\$EX_i * (1 + DISCOUNT)^{-i} \qquad \text{(B-3)}$$

where:

itc = The index representing the technology under consideration
FE = The fuel economy of technology *itc*
DEL$FE = The fractional change in fuel economy associated with technology *itc*
PAYBACK = The user-specified payback period
DISCOUNT = The user-specified discount rate

4) Calculate the cost of technology *itc*:

$$TECHCOST_{itc} = DEL\$COSTABS_{itc} - (DEL\$COSTWGT_{itc} * DEL\$WGTWGT_{itc} * WEIGHT_{BASEYR}) \quad \text{(B-4)}$$

where:

DEL$COSTABS = The fixed dollar cost of technology *itc*
DEL$COSTWGT = The weight-based change in cost ($/lb)
DEL$WGTWGT = The fractional change in weight associated with technology *itc*
WEIGHT = The original vehicle weight

5) Calculate the perceived value of performance associated with technology *itc*:

$$VAL\$PERF_{itc} = VALUEPERF_{itc} * \frac{INCOME_{YEAR}}{INCOME_{YEAR-1}} * \frac{FE_{YEAR-1} * (1 + DEL\$FE_{itc})}{FE_{YEAR-1}} * \frac{FUELCOST_{YEAR-1}}{PRICE\$EX_{1}} * DEL\$HP_{itc} \quad \text{(B-5)}$$

where:

VAL$PERF = The dollar value of performance of technology *itc*
VALUEPERF = The value associated with an incremental change in performance
DEL$HP = The fractional change in horsepower of technology *itc*
PRICE$EX = The expected price of fuel
FUELCOST = The actual price of fuel (in the previous year)

6) Calculate the cost effectiveness of technology *itc*:

$$COSTEFFECT_{itc} = \frac{FUELSAVE_{itc} - TECHCOST_{itc} + VAL\$PERF_{itc} + (REGCOST * FE_{YEAR-1} * DEL\$FE_{itc})}{ABS(TECHCOST_{itc})} \quad \text{(B-6)}$$

where:

COSTEFFECT = A unitless measure of cost effectiveness
REGCOST = A factor representing regulatory pressure to increase fuel economy
TECHCOST = The cost of the considered technology
VAL$PERF = The performance value associated with technology *itc*

7) Calculate the preliminary economic market share of technology *itc*:

$$ACTUAL\$MKT_{itc} = MMAX_{itc} * PMAX_{itc} * \left(1 + e^{-2 * COSTEFFECT_{itc}}\right)^{-1} \quad \text{(B-7)}$$

where:

ACTUAL$MKT = The economic share, prior to consideration of engineering or regulatory constraints. The subsequent adjusted value is stored in the variable MKT$PEN.

MMAX = The maximum market share for technology *itc*, obtained from MKT$MAX

PMAX = The institutional maximum market share, which models tooling constraints on the part of the manufacturers, and is set in the subroutine FUNCMAX.

8) Ensure that existing technologies maintain market share in the absence of competing technologies:

$$ACTUAL\$MKT_{itc} = MAX\left(MKT\$PEN_{YEAR-1}, ACTUAL\$MKT_{itc}\right) \quad \text{(B-8)}$$

where:

$MKT\$PEN_{Year-1}$ = The previous year's market share of technology *itc*

9) Apply mandatory constraints:

$$ACTUAL\$MKT_{itc} = MAX\left(ACTUAL\$MKT_{itc}, MANDMKSH_{itc}\right) \quad \text{(B-9)}$$

where:

MANDMKSH = The minimum market share of technology *itc* required by legislative mandate.

10) Apply required engineering constraints (following a call to the subsequent subroutine NOTE$SUPER):

a) Sum the market shares of the required technologies (*req*):

$$REQ\$MKT = MIN\left(\sum_{req} ACTUAL\$MKT_{req}, 1.0\right) \quad \text{(B-10)}$$

where:

REQ$MKT = The total market share of those technologies which are required for the implementation of technology *itc*, indicating that technology's maximum share

b) Compare REQ$MKT to the market share of technology referred to by the engineering note, $ACTUAL\$MKT_{itc}$, selecting the smaller share:

$$ACTUAL\$MKT_{itc} = MIN\left(ACTUAL\$MKT_{itc}\ ,\ REQ\$MKT\right) \qquad \text{(B-11)}$$

11) Assign the preliminary market share value to the permanent variable:

$$MKT\$PEN_{icl,igp,itc,year} = ACTUAL\$MKT_{itc} \qquad \text{(B-12)}$$

where:

MKT$PEN = The market penetration of technology *itc* by vehicle group *igp* and vechilce class *icl*

12) Apply synergistic engineering constraints to those technologies whose combination provide non-additive benifits to fuel economy:

$$FE_{YEAR} = FE_{YEAR} + \left(MKT\$PEN_{itc1,YEAR} - MKT\$PEN_{itc1,YEAR-1}\right) * \left(MKT\$PEN_{itc2,YEAR} - MKT\$PEN_{itc2,YEAR-1}\right) * SYNR\$DEL_{itc1,itc2} \qquad \text{(B-13)}$$

where:

itc1 = First synergistic technology

itc2 = Second synergistic technology

SYNR$DEL = The synergistic effect of the two technologies on fuel economy

13) Calculate the change in market share for a given technology:

$$DELTA\$MKT_{itc} = MKT\$PEN_{itc,YEAR} - MKT\$PEN_{itc,YEAR-1} \qquad \text{(B-14)}$$

where:

$DELTA\$MKT_{itc}$ = The change in market share for technology *itc*

14) Calculate current fuel economy for the considered vehicle class:

$$FE_{YEAR} = FE_{YEAR-1} + \sum_{itc=1}^{NUMTECH} FE_{YEAR-1} * DELTA\$MKT_{itc} * DEL\$FE_{itc} \qquad \text{(B-15)}$$

where:

DEL$FE*itc* = The fractional change in fuel economy attributed to technology *itc*

15) Calculate average vehicle weight for the considered class:

$$WEIGHT_{YEAR} = WEIGHT_{YEAR-1} + \sum_{itc=1}^{NUMTECH} DELTA\$MKT_{itc} * \left[DEL\$WGTABS_{itc} + \left(WEIGHT_{BASEYR} * DEL\$WGTWGT_{itc}\right)\right] \quad \text{(B-16)}$$

where:

DEL$WGTABS = The change in weight (lbs) associated with technology *itc*

DEL$WGTWGT = The fractional change in vehicle weight due to technology *itc*

$WEIGHT_{BASEYEAR}$ = The base year vehicle weight, absent the considcred technology

16) Calculate the average vehicle price for the considered class:

$$PRICE_{YEAR} = PRICE_{YEAR-1} + \sum_{itc=1}^{NUMTECH} DELTA\$MKT_{itc} * \left[DEL\$COSTABS_{itc} + \left(WEIGHT_{YEAR} - WEIGHT_{BASEYR}\right) * DEL\$COSTWGT_{itc}\right] \quad \text{(B-17)}$$

where:

DEL$COSTABS = The cost of technology *itc*

DEL$COSTWGT = The weight-based change in cost of technology *itc* ($/lb)

17) Calculate horsepower, assuming a constant weight to horsepower ratio:

$$HP_{YEAR} = HP_{BASEYR} * \frac{WEIGHT_{YEAR}}{WEIGHT_{BASEYR}} \quad \text{(B-18)}$$

where:

$HP_{BASEYEAR}$ = The base year average horseposer for the considered vehicle class

18) Calculate the horsepower adjustment factor:

$$ADJHP = PERFFACT * \left[\left(\frac{INCOME_{YEAR}}{INCOME_{YEAR-1}}\right)^{0.8} * \left(\frac{PRICE_{YEAR-1}}{PRICE_{YEAR}}\right)^{0.8} * \left(\frac{FE_{YEAR}}{FE_{YEAR-1}}\right)^{0.2} * \left(\frac{FUELCOST_{YEAR-1}}{FUELCOST_{YEAR}}\right)^{0.2} - 1\right] \quad \text{(B-19)}$$

where:

ADJHP = The fractional change in horspower from the previous year within a given vehicle class
INCOME = Household income
PRICE = Vehicle price
FE = Vehicle fuel economy
FUELCOST = Fuel price

19) Calculate current year horsepower, summing incremental changes from the initial year:

$$HP_{YEAR} = HP_{YEAR} * \left(1 + \sum_{1990}^{YEAR} ADJHP\right) \quad \text{(B-20)}$$

20) Calculate fractional change in fuel economy due to horsepower change:

$$ADJFE = -0.22 * ADJHP - 0.560 * ADJHP^2 \; ; \; ADJHP \geq 0$$
$$ADJFE = -0.22 * ADJHP + 0.560 * ADJHP^2 \; ; \; ADJHP < 0 \quad \text{(B-21)}$$

where:

ADJFE = The fuel economy adjustment factor

21) Calculate the adjusted fuel economy:

$$FE = FE * (1 + ADJFE) \quad \text{(B-22)}$$

22) Calculate the vehicle price, adjusted for the change in performance:

$$PRICE = PRICE + ADJHP * VALUEPERF \quad \text{(B-23)}$$

FUEL ECONOMY MODEL — Subroutine NOTE$SUPER

This subroutine is called from subroutine FEMCALC in order to check whether new technologies have superseded older ones. Affected technologies are grouped in a hierarchy, and market shares are adjusted so that the sum does not exceed the maximum market penetration of the group.

1) Calculate aggregate market share of superseding technologies:

$$TOT\$MKT = \sum_{ino=1}^{num\$sup} ACTUAL\$MKT_{ino} \quad \text{(B-24)}$$

where:

TOT$MKT = The total market share of the considered group of technologies
ino = The index identifying the technologies in the superseding group
num$sup = The number of technologies in the superseding group

2) Establish the maximum market share for the group:

--where:

$$MAX\$SHARE = MAX\,(MKT\$MAX_{ino}) \quad \text{(B-25)}$$

MKT$MAX = The maximum market share for the considered technology, exogenously set
MAX$SHARE = The maximum market share of the group, *ino*

3) If the aggregate market share (TOT$MKT) is greater than the maximum share (MAX$SHARE), reduce the market shares of those technologies which are lower in the hierarchy:

a) Calculate the reduction in market share of a superseded technology, ensuring that the decrement does not exceed that technology's total share:

$$DEL\$MKT = MIN\,((TOT\$MKT - MAX\$SHARE),\ ACTUAL\$MKT_{isno}) \quad \text{(B-26)}$$

where:

DEL$MKT = The amount of the superseded technology's market share to be removed
isno = An index indicating the superseded technology

b) Adjust total market share to reflect this decrement

$$TOT\$MKT = TOT\$MKT - DEL\$MKT \quad \text{(B-27)}$$

c) Adjust the market share of the superseded technology to reflect the decrement

$$ACTUAL\$MKT_{isno} = ACTUAL\$MKT_{isno} - DEL\$MKT \quad \text{(B-28)}$$

These values are returned to the preceding subroutine.

1) Calculate incremental change in class market share ratio:

a) For all vehicles except luxury cars:

$$DIFF\$LN = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR} - \$13{,}000}{INCOME_{1990} - \$13{,}000}\right) \quad \text{(B-29)}$$

where:

DIFF$LN = The increment from the base year (1990) of the log of the market share ratio

b) For luxury cars:

$$DIFF\$LN = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR}}{INCOME_{1990}}\right) \quad \text{(B-30)}$$

2) Solve for the log-share ratio:

$$RATIO\$LN = DIFF\$LN + \ln\left(\frac{CLASS\$SHARE_{1990}}{1 - CLASS\$SHARE_{1990}}\right) \quad \text{(B-31)}$$

where:

RATIO$LN = Log of the market share ratio of the considered vehicle class

3) Solve for the class market share:

$$CMKS = \frac{EXP\ (RATIO\$LN)}{1 + EXP\ (RATIO\$LN)} \quad \text{(B-32)}$$

where:

CMKS = Class market share, subsequently reassigned to the appropriate vehicle class and group, $CLASS\$SHARE_{icl,igp}$

4) Normalize so that shares total 100% within each CAFE group:

$$\mathbf{CLASS\$SHARE}_{icl,igp,YEAR} = \frac{\mathbf{CLASS\$SHARE}_{icl,igp,YEAR}}{\sum_{icl=1}^{7} \mathbf{CLASS\$SHARE}_{icl,igp,YEAR}} \qquad \textbf{(B-33)}$$

FUEL ECONOMY MODEL — Subroutine CAFECALC

1) Calculate the Corporate Average Fuel Economy for each of the four CAFE groups:

$$\mathbf{CAFE}_{icl,igp,YEAR} = \frac{\sum_{icl=1}^{7} \mathbf{CLASS\$SHARE}_{icl,igp,YEAR}}{\sum_{icl=1}^{7} \frac{\mathbf{CLASS\$SHARE}_{icl,igp,YEAR}}{\mathbf{FE}_{icl,igp,YEAR}}} \qquad \textbf{(B-34)}$$

where:

icl = FEM vehicle size class index (7)

igp = CAFE group index: 1 = domestic car, 2 = import car, 3 = domestic light truck, 4 = import light truck

REGIONAL SALES MODEL — Subroutine FEMSIZE

This subroutine maps vehicle sales and fuel economy generated for the seven size classes considered in the Fuel Economy Model (FEM) into the six vehicle size classes used in subsequent sectors.

1) Map vehicle sales from seven size classes to six:

$$\mathbf{MAPSALE}_{igp,icl,osc,N} = \mathbf{NVS7SC}_{igp,icl,N} * \mathbf{MAP}_{igp,icl,osc} \qquad \textbf{(B-35)}$$

where:

MAPSALE = Disaggregate vehicle sales

NVS7SC = New vehicle sales within the seven FEM size classes, calculated in subroutine TSIZE

MAP = Array of mapping constants, which converts FEM to ORNL size classes

osc = ORNL size class index (6)

N = Time period index (1990 = 1)

2) Sum across sales within each size class:

$$TOTNVS7 = \sum_{icl=1}^{7} MAPSALE_{igp,icl,oac,N} \quad \text{(B-36)}$$

where:

TOTNVS7 = Total new vehicle sales within the six ORNL size classes

3) Create a mapping share:

$$MAPSHR_{igp,icl,oac,N} = \frac{MAPSALE_{igp,icl,oac,N}}{TOTNVS7_{igp,oac,N}} \quad \text{(B-37)}$$

where:

MAPSHR = Sales shares within the disaggregate array

4) Multiply MPG by mapped sales share:

$$FEMPG_{igp,oac,N} = \sum_{icl=1}^{7} FE_{icl,igp,YEAR} * MAPSHR_{igp,icl,oac,N} \quad \text{(B-38)}$$

where:

FEMPG = Average fuel economy by six ORNL size classes

FE = Average fuel economy by seven FEM size classes

$YEAR$ = Year index ($YEAR = N+1$)

5) Create benchmark factors for each CAFE group *igp*, held constant after 1992:

$$BENCHMPG_{igp,oac} = \frac{ORNLMPG_{igp,oac}}{FEMPG_{igp,oac,N-6}} \quad \text{(B-39)}$$

where:

BENCHMPG = MPG benchmark factors to ensure congruence with most recent data from ORNL

ORNLMPG = Most recent (1992) fuel economy data from ORNL

6) Apply the benchmark factor to each size class, combining domestic and imported vehicles:

$$FESIXC_{osc,N} = \sum_{igp=1}^{2} FEMPG_{igp,osc,N} * BENCHMPG_{igp,osc} * ORNLSHR_{igp,osc}$$

$$FESIXT_{osc,N} = \sum_{igp=3}^{4} FEMPG_{igp,osc,N} * BENCHMPG_{igp,osc,} * ORNLSHR_{igp,osc} \quad \text{(B-40)}$$

where:

FESIXC = Fuel economy for cars within six size classes

FESIXT = Fuel economy for light trucks within six size classes

REGIONAL SALES MODEL — Subroutine TSIZE

1) Estimate non-fleet, non-commercial sales of cars and light-trucks within each of the seven size classes considered by FEM (subsequently passed to subroutine FEMSIZE):

a) For cars, *igp* = 1,2:

$$NVS7SC_{igp,icl,N} = CLASS\$SHARE_{icl,igp,YEAR} * TMC_SQTRCARS_N * (1 - FLTCRAT_{1990}) * SALESHR_{igp,N} \quad \text{(B-41)}$$

where:

NVS7SC = New vehicle sales in the original seven FEM size classes, by CAFE group *igp*

TMC_SQTRCARS = Total new car sales (supplied by the MACRO module)

CLASS$SHARE = The market share for each automobile class, from FEM

FLTCRAT = Fraction of new cars purchased by fleets

SALESHR = Fraction of vehicle sales which are domestic/imported

b) For light trucks, *igp* = 3,4:

$$NVS7SC_{igp,icl,N} = CLASS\$SHARE_{icl,igp,YEAR} * TMC_SQDTRUCKS_N * (1 - (FLTTRAT_{1990} + COMTSHR)) * SALESHR_{igp,N} \quad \text{(B-42)}$$

where:

TMC_SQDTRUCKS = Total new light truck sales (from the MACRO module)

FLTTRAT = Fraction of new light trucks purchased by fleets

COMTSHR = Fraction of new light trucks dedicated to commercial freight

2) Redistribute car and truck sales among six size classes, combining import and domestic:

a) For cars:

$$NCSTSCC_{osc,N} = \sum_{igp=1}^{2} \sum_{icl=1}^{7} \left(NVS7SC_{igp,icl,N}\right) * MAP_{igp,icl,osc} \qquad \text{(B-43)}$$

where:

NCSTSCC = Total new car sales by size class *osc*

MAP = Array of constants which map sales from seven to six size classes

b) For light trucks:

$$NLTSTSCC_{osc,N} = \sum_{igp=3}^{4} \sum_{icl=1}^{7} \left(NVS7SC_{igp,icl,N}\right) * MAP_{igp,icl,osc} \qquad \text{(B-44)}$$

where:

NLTSTSCC = Total new light truck sales by size class *osc*

3) Calculate the market shares of cars and light trucks by size class:

$$PASSHRR_{osc,N} = \frac{NCSTSCC_{osc,N}}{\sum_{osc=1}^{6} NCSTSCC_{osc,N}} \qquad \text{(B-45)}$$

and:

$$LTSHRR_{osc,N} = \frac{NLTSTSCC_{osc,N}}{\sum_{osc=1}^{6} NLTSTSCC_{osc,N}} \qquad \text{(B-46)}$$

where:

PASSHRR = Non-fleet market shares of automobiles, by size class *osc*

NLTSHRR = Non-fleet market shares of light trucks, by size class *osc*

4) Reassign horsepower estimates to six size classes:

$$HPCAR_{osc,N} = \sum_{igp=1}^{2} \sum_{icl=1}^{7} \left(HP_{icl,igp,YEAR}\right) * SALESHR_{igp} * MAP_{igp,icl,osc} \quad \text{(B-47)}$$

and:

$$HPTRUCK_{osc,N} = \sum_{igp=3}^{4} \sum_{icl=1}^{7} \left(HP_{icl,igp,YEAR}\right) * SALESHR_{igp} * MAP_{igp,icl,osc} \quad \text{(B-48)}$$

where:

HPCAR = Average horsepower of automobiles, by size class *osc*

HPTRUCK = Average horsepower of light trucks, by size class *osc*

HP = Vehicle horsepower by FEM size class *icl* and CAFE group *igp*

SALESHR = Domestic vs. import market share for automobiles and light trucks, from ORNL

5) Calculate average horsepower of cars and light trucks, by size class *osc*:

$$AHPCAR_N = \sum_{osc=1}^{6} HPCAR_{osc,N} * PASSHRR_{osc,N} \quad \text{(B-49)}$$

and:

$$AHPTRUCK_N = \sum_{osc=1}^{6} HPTRUCK_{osc,N} * LTSHRR_{osc,N} \quad \text{(B-50)}$$

where:

AHPCAR = Average automobile horsepower

AHPTRUCK = Average light truck horsepower

1) Calculate regional shares of fuel demand, and normalize:

$$SEDSHR_{FUEL,REG,T} = \frac{SEDSHR_{FUEL,REG,T-1} * \left(\frac{TMC_YD_{REG,T}}{TMC_YD_{REG,T-1}}\right)}{\sum_{REG=1}^{9} SEDSHR_{FUEL,REG,T-1} * \left(\frac{TMC_YD_{REG,T}}{TMC_YD_{REG,T-1}}\right)} \quad \text{(B-51)}$$

where:

SEDSHR = Regional share of the consumption of a given fuel in period *T*
TMC_YD = Estimated disposable personal income by region, *REG* (9)
FUEL = Index of fuel type (11)

2) Calculate regional cost of driving per mile:

$$COSTMIR_{REG,T} = 0.1251 * \left(\frac{TPMGTR_{REG,T}}{MPGFLT_{T-1}}\right) \quad \text{(B-52)}$$

where:

COSTMIR = The cost per mile of driving in region *REG*, in $/mile
TPMGTR = The regional price of motor gasoline, in $/MMBTU
MPGFLT = The previous year's stock MPG for non-fleet vehicles
.1251 = A conversion factor for gasoline, in MMBTU/gal

3) Calculate regional income:

$$INCOMER_{REG,T} = \left(\frac{TMC_YD_{REG,T}}{TMC_POPAFO_{REG,T}}\right) \quad \text{(B-53)}$$

where:

INCOMER = Regional per capita disposable income
TMC_POPAFO = Total population in region *REG*

4) Estimate regional driving demand:

$$VMT16R_{REG,T} = \rho\, VMT16R_{REG,T-1} + \beta_0 (1 - \rho) + \beta_1 \left(COSTMIR_{REG,T} - \rho\, COSTMIR_{REG,T-1}\right) \quad \text{(B-54)}$$
$$+\beta_2 \left(INCOMER_{REG,T} - \rho\, INCOMER_{REG,T-1}\right) + \beta_3 \left(PRFEM_T - \rho\, PRFEM_{T-1}\right)$$

and:

$$VMTEER_{REG,T} = VMT16R_{REG,T} * TMC_POP16_{REG,T} * DAF_T \quad \text{(B-55)}$$

where:

VMT16R = Vehicle-miles traveled per population over 16 years of age
PRFEM = Ratio of female to male driving rates
ρ = Lag factor for the difference equation
VMTEER = Total VMT in region *REG*
TMC_POP16 = Total regional population over the age of 16
DAF = A demographic adjustment factor, to reflect different age groups' driving patterns

5) Calculate regional VMT shares (RSHR):

$$RSHR_{REG,T} = \frac{VMTEER_{REG,T}}{\sum_{REG=1}^{9} VMTEER_{REG,T}} \quad \text{(B-56)}$$

6) Divide non-fleet car and light truck sales according to regional VMT shares:

$$NCS_{REG,SC,T} = NCSTSCC_{SC,T} * RSHR_{REG,T} \quad \text{(B-57)}$$

and:

$$NLTS_{REG,SC,T} = NLTSTSCC_{SC,T} * RSHR_{REG,T} \quad \text{(B-58)}$$

where:

NCS = New car sales, by size class *SC* and region *REG*
NLTS = New light truck sales, by size class and region

1) Calculate commercial availability by technology:

$$COMAV_{IT,N} = \left[1 + EXP\left(\frac{TT50_{IT} - YEAR}{2}\right)\right]^{-1} \quad \text{(B-59)}$$

where:

COMAV = The fraction of market demand of a given technology which is commercially available

IT = Index of the sixteen engine technologies considered by the model

TT50 = The exogenously specified year in which 50% of the demand for technology *IT* can be met

2) Calculate the weighted average fuel price for each technology, by region:

$$AFCOST_{IT,IR,N} = \frac{\sum_{FUEL} (RFP_{FUEL,IR,N} \cdot FAVAIL_{FUEL,IR,N})}{\sum_{FUEL} FAVAIL_{FUEL,IR,N}} \quad \text{(B-60)}$$

where:

AFCOST = Weighted average fuel price, in 1990 cents/MMBTU, for each technology *IT*

RFP = Price of each fuel used by the corresponding technology

FAVAIL = Relative availability of the corresponding fuel

3) Map fuel economy for cars and light trucks from six to three size classes for use in the AFV model:

a) For cars:

$$FEC3SC_{ISC,N} = \left[\frac{\sum_{OSC}\left(\frac{NCSTSCC_{OSC,N}}{FESIXC_{OSC,N}}\right)}{\sum_{OSC} NCSTSCC_{OSC,N}}\right]^{-1} \quad \text{(B-61)}$$

where:

FEC3SC = Automobile fuel economy within the three reduced size classes

NCSTSCC = New car sales within the six size classes *OSC*

FESIXC = New car fuel economy within the six size classes *OSC*

ISC = Index of reduced size classes, mapped as follows for cars: *ISC* = 1, *OSC* = 2, 3; *ISC* = 2, *OSC* = 1, 6; *ISC* = 3, *OSC* = 4, 5

b) For light trucks:

$$FET3SC_{ISC,N} = \left[\frac{\sum_{OSC} \left(\frac{NLTSTSCC_{OSC,N}}{FESIXT_{OSC,N}} \right)}{\sum_{OSC} NLTSTSCC_{OSC,N}} \right]^{-1} \quad \text{(B-62)}$$

where:

FET3SC = Light truck fuel economy within the three reduced size classes

NLTSTSCC = New light truck sales within the six size classes *OSC*

FESIXT = New light truck fuel economy within the six size classes *OSC*

ISC = Index of reduced size classes, mapped as follows for trucks: *ISC* = 1, *OSC* = 1, 3; *ISC* = 2, *OSC* = 2, 5; *ISC* = 3, *OSC* = 4, 6

4) Convert fuel economy from miles per gallon to miles per MMBTU:

$$VEFFACT_{ISC,N} = \frac{FEC3SC_{ISC,N}}{0.125} \quad \text{(B-63)}$$

where:

VEFFACT = Gasoline vehicle fuel economy, used as a baseline

5) Calculate alternative vehicle fuel economy, using gasoline baseline:

$$VEFFBTU_{ISC,IT,N} = VEFF_{ISC,IT,N} * VEFFACT_{ISC,N} \quad \text{(B-64)}$$

where:

VEFFBTU = Fuel economy by technology *IT*, in miles per MMBTU

VEFF = Fuel economy of technology *IT*, relative to gasoline baseline

6) Calculate AFV operating cost, by region:

$$COPCOST_{IT,ISC,IR,N} = \frac{AFCOST_{IT,IT,N} * 100}{VEFFBTU_{ISC,IT,N}} \quad \text{(B-65)}$$

where:

COPCOST = Regional vehicle operating cost, in 1990$/mile

7) Calculate utility of electric and electric hybrid vehicles (*IT* = 7-10):

where:

$$VC3_{IT,IR} = BETACONST_{IT} + BETAVP \cdot VPRICE3_{IS,IT,N} + BETAFC \cdot COPCOST3_{IT,IS,IR,N} + BETAVR \cdot VRANGE3_{IS,IT,N} + BETAVR2 \cdot VRANGE3^2_{IS,IT,N} + BETAEM \cdot EMISS3_{IS,IT,N} + BETAEM2 \cdot EMISS3^2_{IS,IT,N} + BETAFA \cdot FAVAIL3_{IT,IR,N} + BETAFA2 \cdot FAVAIL3^2_{IT,IR,N} \quad \text{(B-66)}$$

VC3 = Utility vector for electric vehicles
BETACONST = Constant associated with each considered technology *IT*
COPCOST3 = Fuel operating costs for electric vehicles
VPRICE3 = Price of each considered EV technology in 1990$
VRANGE3 = Vehicle range of the considered EV technology
EMISS3 = EV emissions levels relative to gasoline ICE's
FAVAIL33 = Fuel availability for EV technologies
BETAVP = Coefficient associated with vehicle price
VETAFC = Coefficient associated with fuel cost
BETAVR = Coefficient associated with vehicle range
BETAEM = Coefficient associated with vehicle emissions
BETAFA = Coefficient associated with fuel availability
BETAVR2 = Coefficient associated with the square of vehicle range
BETAEM2 = Coefficient associated with the square of vehicle emissions
BETAFA2 = Coefficient associated with the square of fuel availability

8) Exponentiate utility vector, and adjust by commercial availability factor:

$$EVC3_{IT,IS,IR,N} = EXP\left[VC3_{IT,IS,IR,N}\right] * COMAV_{IT,N} \quad \text{(B-67)}$$

where:

EVC3 = Exponentiated value of electric vehicle utility vector

9) Calculate electric vehicle market shares, by region:

$$APSHR33_{IS,IR,IT,N} = \frac{EVC3_{IT,IS,IR,N}}{\sum_{IT=1}^{10} EVC3_{IT,IS,IR,N}} \quad \text{(B-68)}$$

where:

APSHR33 = Relative market shares within the electric vehicle group

1) Calculate weighted average characteristics of electric vehicles, and reconfigure technology indices to reflect the compression of four EV technologies into one prototype:

$$\Psi_{IS,IT,IR,N} = \sum_{IT=7}^{10} \Psi_{IS,IT,IR,N} \cdot APSHR33_{IS,IR,IT,N} \qquad \text{(B-69)}$$

where:

Ψ = VPRICE3, VEMISS3, VRANGE3, COMAV, COPCOST, FAVAIL33, and BETACONST

2) Calculate utility for alternative fuel vehicles (IT = 3-13):

$$\begin{aligned} VC2_{IT,IR} = {} & BETACONST2_{IT} + BETAVP \cdot VPRICE2_{IS,IT,N} + BETAFC \cdot COPCOST2_{IT,IS,IR,N} \\ & + BETAVR \cdot VRANGE2_{IS,IT,N} + BETAVR2 \cdot VRANGE2^2_{IS,IT,N} + BETAEM \cdot EMISS2_{IS,IT,N} \\ & + BETAEM2 \cdot EMISS2^2_{IS,IT,N} + BETAFA \cdot FAVAIL22_{IT,IR,N} + BETAFA2 \cdot FAVAIL22^2_{IT,IR,N} \end{aligned} \qquad \text{(B-70)}$$

where:

VC2 = Utility vector for alternative vehicles
BETACONST2 = Constant associated with each considered AFV technology
COPCOST2 = Fuel operating costs for alternative vehicles
VPRICE2 = Price of each considered AFV technology in 1990$
VRANGE2 = Vehicle range of the considered AFV technology
EMISS2 = AFV emissions levels relative to gasoline ICE's
FAVAIL22 = Alternative fuel availability

3) Exponentiate utility vector, and adjust by commercial availability factor:

$$EVC2_{IT,IS,IR,N} = EXP\left[VC2_{IT,IS,IR,N}\right] * COMAV_{IT,N} \qquad \text{(B-71)}$$

where:

EVC2 = Exponentiated value of alternative vehicle utility vector

4) Calculate alternative vehicle market shares, by region:

$$APSHR22_{IS,IR,IT,N} = \frac{EVC2_{IT,IS,IR,N}}{\sum_{IT=3}^{13} EVC2_{IT,IS,IR,N}} \qquad \text{(B-72)}$$

where:

APSHR22 = Relative market shares within the alternative vehicle group

ALTERNATIVE FUEL VEHICLE MODEL Subroutine TALT1

1) Calculate weighted average characteristics of alternative vehicles, and reconfigure technology indices to reflect the compression of eleven alternative technologies into one prototype:

$$\Psi_{IS,IT,IR,N} = \sum_{IT=4}^{13} \Psi_{IS,IT,IR,N} \cdot APSHR22_{IS,IR,IT,N} \quad \text{(B-73)}$$

where:

Ψ = VPRICE2, VEMISS2, VRANGE2, COMAV, COPCOST2, FAVAIL22, and BETACONST2

2) Calculate utility for all vehicles (IT = 1-3):

$$\begin{aligned} VC1_{IT,IR} = {} & BETACONST1_{IT} + BETAVP \cdot VPRICE1_{IS,IT,N} + BETAFC \cdot COPCOST1_{IT,IS,IR,N} \\ & + BETAVR \cdot VRANGE1_{IS,IT,N} + BETAVR2 \cdot VRANGE1^2_{IS,IT,N} + BETAEM \cdot EMISS1_{IS,IT,N} \\ & + BETAEM2 \cdot EMISS1^2_{IS,IT,N} + BETAFA \cdot FAVAIL11_{IT,IR,N} + BETAFA2 \cdot FAVAIL11^2_{IT,IR,N} \end{aligned} \quad \text{(B-74)}$$

where:

VC1 = Utility vector for conventional and alternative vehicles
BETACONST1 = Constant associated with each considered technology
COPCOST1 = Fuel operating costs for conventional and alternative vehicles
VPRICE1 = Price of each considered technology in 1990$
VRANGE1 = Vehicle range of the considered technology
EMISS1 = Emissions levels relative to gasoline ICE's
FAVAIL11 = Fuel availability

3) Exponentiate utility vector, and adjust by commercial availability factor:

$$EVC1_{IT,IS,IR,N} = EXP\left[VC1_{IT,IS,IR,N}\right] * COMAV_{IT,N} \quad \text{(B-75)}$$

where:

EVC1 = Exponentiated value of vehicle utility vector

4) Calculate vehicle market shares, by region:

$$APSHR11_{IS,IR,IT,N} = \frac{EVC1_{IT,IS,IR,N}}{\sum_{IT=1}^{3} EVC1_{IT,IS,IR,N}} \quad \text{(B-76)}$$

where:

APSHR11 = Relative market shares of conventional and alternative vehicles

5) Expand market share estimates to generate absolute market shares for each of the sixteen conventional and alternative technologies:

a) For conventional vehicles (*IT* = 16,15; *IT1* = 1,2):

$$APSHR44_{IS,IR,IT,N} = APSHR11_{IS,IR,IT1,N} * APSHR22_{IS,IR,IT2,N} \quad \text{(B-77)}$$

where:

APSHR44 = Absolute market share of technology *IT*

b) For non-electric alternative vehicles (*IT* = 1-6,11-14; *IT1* = 3; *IT2* = 5,6,3,4,8-13):

$$APSHR44_{IS,IR,IT,N} = APSHR11_{IS,IR,IT1,N} \quad \text{(B-78)}$$

c) For electric and electric hybrid vehicles (*IT* = 7-10; *IT1* = 3; *IT2* = 7; *IT3* = 1-4):

$$APSHR44_{IS,IR,IT,N} = APSHR11_{IS,IR,IT1,N} * APSHR22_{IS,IR,IT2,N} * APSHR33_{IS,IR,IT3,N} \quad \text{(B-79)}$$

LIGHT DUTY VEHICLE FLEET MODULE — Subroutine TFLTSTKS

1) Calculate fleet acquisitions of cars and light trucks:

$$FLTSAL_{VT=1,ITY,T} = FLTCRAT * SQTRCARS_T * FLTCSHR_{ITY}$$

and: (B-80)

$$FLTSAL_{VT=2,ITY,T} = FLTTRAT * SQDTRUCKSL_T * FLTTSHR_{ITY}$$

where:

FLTSAL = Sales to fleets by vehicle and fleet type
FLTCRAT = Fraction of total car sales attributed to fleets
FLTTRAT = Fraction of total truck sales attributed to fleets
SQTRCARS = Total automobile sales in a given year
SQTRUCKSL = Total light truck sales in a given year
FLTCSHR = Fraction of fleet cars purchased by a given fleet type
FLTTSHR = Fraction of fleet trucks purchased by a given fleet type
VT = Index of vehicle type: 1 = cars, 2 = light trucks
ITY = Index of fleet type: 1 = business, 2 = government, 3 = utility

2) Determine total alternative fuel fleet vehicle sales, using either the market-driven or legislatively mandated values :

$$FLTALT_{VT,ITY,T} = MAX\left[\left(FLTSAL_{VT,ITY,T} * FLTAPSHR1_{ITY}\right), EPACT_{VT,ITY,T}\right] \quad \text{(B-81)}$$

where:

FLTALT = Number of AFV's purcnased by each fleet type in a given year
FLTAPSHR1 = Fraction of each fleets' purchases which are AFV's, from historical data
EPACT = Legislative mandates for AFV purchases, by fleet type

3) Calculate the difference between total sales and AFV sales (representing conventional sales):

$$FLTCONV_{VT,ITY,T} = FLTSAL_{VT,ITY,T} - FLTALT_{VT,ITY,T} \quad \text{(B-82)}$$

where:

FLTCONV = Fleet purchases of conventional vehicles

4) Distribute fleet purchases among three size classes:

$$FLTSLSCA_{VT,ITY,IS,T} = FLTALT_{VT,ITY,T} * FLTSSHR_{VT,ITY,IS}$$

and: (B-83)

$$FLTSLSCC_{VT,ITY,IS,T} = FLTCONV_{VT,ITY,T} * FLTSSHR_{VT,ITY,IS}$$

where:

FLTSLSCA = Fleet purchases of AFV's, by size class
FLTSLSCC = Fleet purchases of conventional vehicles, by size class
FLTSSHR = Percentage of fleet vehicles in each size class, from historical data
IS = Index of size classes: 1 = small, 2 = medium, 3 = large

5) Disaggregate AFV sales by engine technology:

$$FLTECHSAL_{VT,ITY=1,IS,ITECH,T} = FLTSLSCA_{VT,ITY=1,IS,T} * APSHRFLTB_{VT,ITECH,ITY=1,T}$$

$$FLTECHSAL_{VT,ITY\neq 1,IS,ITECH,T} = FLTSLSCA_{VT,ITY\neq 1,IS,T} * FLTECHSHR_{ITECH,ITY,T} \quad \text{(B-84)}$$

and:

$$FLTECHSAL_{VT,ITY,IS,ITECH=6,T} = FLTSLSCC_{VT,ITY,IS,T}$$

where:

FLTECHSAL = Fleet sales by size, technology, and fleet type
APSHRFLTB = Alternative technology shares for the business fleet
FLTECHSHR = Alternative technology shares for the government and utility fleets
ITECH = Index of engine technologies: 1-5 = alternative fuels (neat), 6 = gasoline

6) Sum sales across size classes:

$$FLTECH_{VT,ITY,ITECH,T} = \sum_{IS=1}^{3} FLTECHSAL_{VT,ITY,IS,ITECH,T} \quad \text{(B-85)}$$

where:

FLTECH = Vehicle purchases by fleet type and technology

7) Calculate survival of older vehicles, and modify vintage array:

$$FLTSTKVN_{VT,ITY,ITECH,IVIN,T} = FLTSTKVN_{VT,ITY,ITECH,IVIN-1,T-1} * SURVFLTT_{VT,IVIN-1}$$

and: **(B-86)**

$$FLTSTKVN_{VT,ITY,ITECH,IVIN-1,T} = FLTECH_{VT,ITY,ITECH,T}$$

where:

FLTSTKVN = Fleet stock by fleet type, technology, and vintage
SURVFLTT = Survival rate of a given vintage

8) Assign fleet vehicles of retirement vintage to another variable, prior to removal from the fleet:

$$OLDFSTK_{VT,ITY,ITECH,RVINT,T} = FLTSTKVN_{VT,ITY,ITECH,RVINT,T} \quad \textbf{(B-87)}$$

where:

OLDFSTK = Old fleet stocks of given types and vintages, transferred to the private sector
RVINT = Retirement vintage of fleet vehicles: If $VT = 1$, $ITY = 1,2,3$, $RVINT = 5,6,7$; If $VT = 2$, $ITY = 1,2,3$, $RVINT = 6,7,6$

9) Calculate total surviving vehicles, by vehicle, fleet type, and engine technology:

$$TFLTECHSTK_{VT,ITY,ITECH,T} = \sum_{IVIN=1}^{6} FLTSTKVN_{VT,ITY,ITECH,IVIN,T} \quad \textbf{(B-88)}$$

where:

TFLTECHSTK = Total stock within each technology and fleet type

10) Calculate grand total of surviving vehicles:

$$TOTFLTSTK_T = \sum_{VT=1}^{2} \sum_{ITY=1}^{3} \sum_{ITECH=1}^{8} TFLTECHSTK_{VT,ITY,ITECH,T} \quad \textbf{(B-89)}$$

where:

TOTFLTSTK = Total of all surviving fleet vehicles

11) Calculate percentage of fleet stock represented by each of the vehicle, fleet types, and engine technologies:

$$VFSTKPF_{VT,ITY,ITECH,T} = \frac{TFLTECHSTK_{VT,ITY,ITECH,T}}{TOTFLTSTK_{T}} \quad \text{(B-90)}$$

where:

VFSTKPF = Share of fleet stock by vehicle type and technology

LIGHT DUTY VEHICLE FLEET MODULE — Subroutine TLEGIS

This subroutine adjusts vehicle sales and market shares to reflect California's legislative mandates on sales of zero-emission vehicles (ZEV's) and ultra-low emission vehicles (ULEV's), which have also been tentatively adopted by New York and Massachusetts.

1) Calculate regional vehicle sales, by technology, within three size classes:

$$VSALES_{IS,IR,IT,N} = \sum_{OSC} APSHR44_{IS,IR,IT,N} * \left(NCS_{IR,OSC,N} + NLTS_{IR,OSC,N}\right) \quad \text{(B-91)}$$

where:

VSALES = Total disaggregate vehicle sales
APSHR44 = Absolute market share of new vehicles, by region, size, and technology
IS = Index of reduced size class (1-3)
OSC = Index of original size class (1-6)
NCS = Regional new car sales within corresponding size classes *OSC*:
IS = 1, *OSC* = 2,3; *IS* = 2, *OSC* = 1,6; *IS* = 3, *OSC* = 4,5
NLTS = Regional new light truck sales within corresponding size classes *OSC*
IS = 1, *OSC* = 1,2; *IS* = 2, *OSC* = 3,4; *IS* = 3, *OSC* = 5,6

2) Calculate total regional sales of electric and electric hybrid vehicles:

$$ELECVSAL_{IR,N} = \sum_{IS=1}^{3} \sum_{IT=7}^{10} VSALES_{IS,IR,IT,N} \quad \text{(B-92)}$$

where:

ELECVSAL = Regional electric vehicle sales

3) Calculate total vehicle sales across all technologies:

$$VSALEST_{IS,IR,N} = \sum_{IT=1}^{16} VSALES_{IS,IR,IT,N} \quad \text{(B-93)}$$

where:

VSALEST = Total regional vehicle sales, by size class

4) Calculate mandated sales of ZEV's and ULEV's by participating state:

$$ZEVST_{ST,N} = (TMC_SQTRCARS_N * STATESHR_{ST,VT=1,N} + TMC_SQDTRUCKSL_N * STATESHR_{ST,VT=2,N}) * ZEV_N \quad \text{(B-94)}$$

and

$$ULEVST_{ST,N} = (TMC_SQTRCARS_N * STATESHR_{ST,VT=1,N} + TMC_SQDTRUCKSL_N * STATESHR_{ST,VT=2,N}) * ULEV_N$$

where:

ZEVST = State-mandated minimum sales of ZEV's
ULEVST = State-mandated minimum sales of ULEV's
TMC_SQTRCARS = Total car sales, from the MACRO module
TMC_SQDTRUCKSL = Total light truck sales, from the MACRO module
STATESHR = Share of national vehicle sales attributed to a given state
ZEV = State-mandated minimum sales share of ZEV's
ULEV = State-mandated minimum sales share of ULEV's
ST = Index of participating state: CA, MA, NY
VT = Index of vehicle type: 1 = cars, 2 = light trucks

5) If mandated sales exceed actual sales, then adjust actual sales as follows:

a) Evenly distribute mandated sales among three size classes:

$$ZEVSTSC_{ST,IS,N} = \frac{ZEVST_{ST,N}}{3} \quad \text{(B-95)}$$

where:

ZEVSTSC = Mandated ZEV sales by size class and state

b) Evenly distribute actual electric vehicle sales among three size classes:

$$ELECVSALSC_{IR,IS,N} = \frac{ELECVSAL_{IR,N}}{3} \quad \text{(B-96)}$$

where:

ELECVSALSC = Regional ZEV sales within corresponding regions

IR = Corresponding regions: *ST* = CA, MA, NY; *IR* = 9,1,2

c) Calculate mandated ZEV sales by EV technology (*IT* = 7-10):

$$AVSALES_{IS,IR,IT,N} = ZEVSTSC_{ST,IS,N} * APSHR33_{IS,IR,IT,N} \quad \text{(B-97)}$$

where:

AVSALES = Regional adjusted vehicle sales by size class

APSHR33 = Relative market shares of electric vehicle technologies

d) Reduce sales of gasoline vehicles (*IT* = 16) to compensate for increased ZEV sales in the affected regions (*IR* = 1,2,9):

$$AVSALES_{IS,IR,IT=16,N} = VSALES_{IS,IR,IT=16,N} - \left(ZEVSTSC_{ST,IS,N} - ELECVSALSC_{IR,IS,N}\right) \quad \text{(B-98)}$$

6) Reassign vehicle sales in unaffected regions (*IR* ≠ 1,2,9):

$$AVSALES_{IS,IR,IT,N} = VSALES_{IS,IR,IT,N} \quad \text{(B-99)}$$

7) Sum adjusted vehicle sales across technologies:

$$AVSALEST_{IS,IR,N} = \sum_{IT=1}^{16} AVSALES_{IS,IR,IT,N} \quad \text{(B-100)}$$

where:

AVSALEST = Total regional adjusted vehicle sales by size class

8) Calculate new absolute market shares for each vehicle technology:

$$APSHR55_{IS,IR,IT,N} = \frac{AVSALES_{IS,IR,IT,N}}{AVSALEST_{IS,IR,N}} \quad \text{(B-101)}$$

where:

APSHR55 = Absolute regional market shares of adjusted vehicle sales

9) Reset conventional vehicle market shares so that diesel represents 2.5% of conventional vehicle sales:

$$APSHR55_{IS,IR,IT=15,N} = \sum_{IT=15}^{16} APSHR55_{IS,IR,IT,N} * 0.025$$

and (B-102)

$$APSHR55_{IS,IR,IT=16,N} = \sum_{IT=15}^{16} APSHR55_{IS,IR,IT,N} * 0.975$$

10) Calculate new fleet market shares for use with business fleets:

a) Calculate total vehicle sales by technology:

$$VSALESC16_{IT,N} = \sum_{IR=1}^{8} \sum_{IS=1}^{3} APSHR55_{IS,IR,IT,N} * \left(\sum_{OSC} NCS_{IR,OSC,N} \right)$$

and (B-103)

$$VSALEST16_{IT,N} = \sum_{IR=1}^{8} \sum_{IS=1}^{3} APSHR55_{IS,IR,IT,N} * \left(\sum_{OSC} NLTS_{IR,OSC,N} \right)$$

where:

VSALESC16 = Total new car sales by technology:

IS = 1, *OSC* = 2,3; *IS* = 2, *OSC* = 1,6; *IS* = 3, *OSC* = 4,5

VSALEST16 = Total new light truck sales by technology

IS = 1, *OSC* = 1,3; *IS* = 2, *OSC* = 2,5; *IS* = 3, *OSC* = 4,6

b) Calculate market shares by technology:

$$APSHRNC_{IT,N} = \frac{VSALESC16_{IT,N}}{\sum_{IT=1}^{16} VSALESC16_{IT,N}}$$

and (B-104)

$$APSHRNT_{IT,N} = \frac{VSALEST16_{IT,N}}{\sum_{IT=1}^{16} VSALEST16_{IT,N}}$$

where:

APSHRNC = Market shares of new cars by technology

APSHRNT = Market shares of new light trucks by technology

c) Sum market shares for affected fleet technologies:

$$APSHRFLTOT_{VT=1,N} = \sum_{ITF} APSHRNC_{ITF,N}$$

and (B-105)

$$APSHRFLTOT_{VT=2,N} = \sum_{ITF} APSHRNT_{ITF,N}$$

where:

APSHRFLTOT = Aggregate market shares of fleet vehicle technologies

VT = Index of vehicle type: 1 = cars; 2 = light trucks

ITF = Index of fleet vehicle technologies, corresponding to *IT* = 3,5,7,8,9

d) Normalize business fleet market shares:

$$APSHRFLTB_{VT=1,ITF,N} = \frac{APSHRNC_{IT,N}}{APSHRFLTOT_{VT=1,N}}$$

and (B-106)

$$APSHRFLTB_{VT=2,ITF,N} = \frac{APSHRNT_{IT,N}}{APSHRFLTOT_{VT=2,N}}$$

where:

APSHRFLTB = Market shares of business fleet by vehicle type and technology

11) Reset new car and light truck sales using market shares, mapped from three to six size

classes:

$$NCSTECH_{IR,OSC,IT,N} = NCS_{IR,OSC,N} * APSHR55_{IS,IR,IT,N}$$

$$\text{and} \qquad (B\text{-}107)$$

$$NLTECH_{IR,OSC,IT,N} = NLTS_{IR,OSC,N} * APSHR55_{IS,IR,IT,N}$$

where:

NCSTECH = Regional new car sales by technology, within six size classes:
OSC = 1-6; *IS* = 2,1,1,3,3,2

NLTECH = Regional light truck sales by technology, with six size classes:
OSC = 1-6; *IS* = 1,2,1,3,2,3

LIGHT DUTY VEHICLE FLEET MODULE — Subroutine TFLTVMTS

This subroutine calculates VMT for fleets.

1) Use historical data on fleet vehicle travel to est ate total fleet VMT:

$$FLTVMT_T = \sum_{VT=1}^{2} \sum_{ITY=1}^{3} \sum_{ITECH=1}^{8} (TFLTECHSTK_{VT,ITY,ITECH,T} * FLTVMTYR_{VT,ITY,T}) \qquad (B\text{-}108)$$

where:

FLTVMT = Total VMT driven by fleet vehicles
FLTVMTYR = Annual miles of travel per vehicle, by vehicle and fleet type
VT = Index of vehicle type: 1 = cars, 2 = light trucks
ITY = Index of fleet type: Business, Government, Utility
ITECH = Index of fleet engine technology, corresponding to *IT* = 3,5,9,7,8

2) Disaggregate total VMT by vehicle type and technology:

$$FLVMTECH_{VT,ITY,ITECH,T} = FLVMT_T * VFSTKPF_{VT,ITY,ITECH,T} \qquad (B\text{-}109)$$

where:

FLTVMTECH = Fleet VMT by technology, vehicle type, and fleet type
VFSTKPF = Share of fleet stock by vehicle type and technology

This subroutine calculates fuel efficiency for the fleet stock

1) Calculate the average efficiencies of the five non-gasoline technologies (*ITECH* = 1-5):

$$FLTMPG_{VT=1,ITY,ITECH} = \left[\sum_{IS=1}^{3} \frac{FMSHC_{ITY,ITECH,IS}}{NAMPG_{IT,IS}} \right]^{-1}$$

and: **(B-110)**

$$FLTMPG_{VT=2,ITY,ITECH} = \left[\sum_{IS=1}^{3} \frac{FMSHLT_{ITY,ITECH,IS}}{NAMPG_{IT,IS} * RATIO_{IS}} \right]^{-1}$$

where:

FLTMPG = New fleet vehicle fuel efficiency, by fleet type and engine technology
FMSHC = The market share of fleet cars, from the AFV model
FMSHLT = The market share of fleet light trucks, from the AFV model
NAMPG = New AFV fuel efficiency, from the AFV model
IT = Index which matches technologies in the AFV model to corresponding *ITECH*:
ITECH = 1-5, *IT* = 4,2,7,5,6
IS = Index of reduced size class (1-3)
VT = Index of vehicle type: 1 = cars, 2 = light trucks

2) Calculate the average efficiencies of conventional vehicles:

$$FLTMPG_{VT=1,ITY,ITECH} = \left[\sum_{IS=1}^{3} \frac{FMSHC_{ITY,ITECH,IS}}{FEC3SC_{IS}} \right]^{-1}$$

and: **(B-111)**

$$FLTMPG_{VT=2,ITY,ITECH} = \left[\sum_{IS=1}^{3} \frac{FMSHLT_{ITY,ITECH,IS}}{FET3SC_{IS}} \right]^{-1}$$

where:

FEC3SC = New car MPG, by three size classes, from the FEM model
FET3SC = New light truck MPG, by three size classes, from the FEM model

3) Calculate the average fleet MPG for cars and light trucks:

$$FLTMPGTOT_{VT,T} = \left[\frac{\sum_{IS=1}^{3} \sum_{ITECH=1}^{8} \frac{FLTECH_{VT,IS,ITECH,N}}{FLTMPG_{VT,IS,ITECH,N}}}{\sum_{IS=1}^{3} \sum_{ITECH=1}^{8} FLTECH_{VT,IS,ITECH,N}} \right]^{-1} \quad \text{(B-112)}$$

where:

FLTMPGTOT = Overall fuel efficiency of new fleet cars and light trucks

4) Adjust vintage array of fleet stock efficiencies to account for new additions:

$$MPGFSTK_{VT,ITY,ITECH,IVIN,T} = MPGFSTK_{VT,ITY,ITECH,IVIN-1,T-1}$$

$$\text{and:} \quad \text{(B-113)}$$

$$MPGFSTK_{VY,ITY,ITECH,IVIN-1,T} = FLTMPG_{VT,ITY,ITECH,T}$$

where:

MPGFSTK = Fleet MPG by vehicle and fleet type, technology, and vintage

IVIN = Index of fleet vintages

5) Calculate average fuel efficiency by vehicle and fleet type:

$$MPGFLTSTK_{VT,ITY,ITECH,T} = \left[\sum_{IVIN=1}^{MAXVINT} \frac{\left(\frac{FLTSTKVN_{VT,ITY,ITECH,IVIN,T}}{MPGFSTK_{VT,ITY,ITECH,IVIN,T} * VDF_{VT}} \right)}{\left(TFLTECHSTK_{VT,ITY,ITECH,T} \right)} \right]^{-1} \quad \text{(B-114)}$$

where:

MPGFLTSTK = Fleet MPG by vehicle and fleet type, and technology, across vintages

MAXVINT = Maximum *IVIN* index associated with a given vehicle and fleet type

VDF = Vehicle degradation factor

TFLTECHSTK = Total fleet stocks by vehicle, fleet type, and technology

6) Calculate overall fleet average MPG for cars and light trucks:

$$FLTTOTMPG_{VT,T} = \left[\sum_{ITY=1}^{3} \sum_{ITECH=1}^{8} \frac{VFSTKPF_{VT,ITY,ITECH,T}}{MPGFLTSTK_{VT,ITY,ITECH,T}} \right]^{-1} \quad \text{(B-115)}$$

where:

FLTTOTMPG = Fleet vehicle average fuel efficiency for cars and light trucks

This subroutine calculates fuel consumption of fleet vehicles.

1) Calculate fuel consumption:

$$FLTLDVC_{VT,ITY,ITECH,T} = \frac{FLTVMTECH_{VT,ITY,ITECH,T}}{MPGFLTSTK_{VT,ITY,ITECH,T}} \quad \text{(B-116)}$$

where:

FLTLDVC = Fuel consumption by technology, vehicle and fleet type

2) Sum consumption across fleet types, and convert to Btu values:

$$FLTFCLDVBTU_{VT,ITECH,T} = \sum_{ITY=1}^{3} FLTLDVC_{VT,ITY,ITECH,T} * QBTU_{ITECH} \quad \text{(B-117)}$$

where:

FLTFCLDVBTU = Fuel consumption, in Btu, by vehicle type and technology

QBTU = Energy content, in Btu/Gal, of the fuel associated with each technology

Consumption by trucks and cars are added, and total consumption is subsequently divided among regions:

$$FLTFCLDVBTUR_{IR,ITECH,T} = \sum_{VT=1}^{2} FLTFCLDVBTU_{VT,ITECH,T} * RSHR_{IR,T} \quad \text{(B-118)}$$

where:

FLTFCLDVBTUR = Regional fuel consumption by fleet vehicles, by technology

RSHR = Regional VMT shares, from the Regional Sales Module

LIGHT DUTY VEHICLE STOCK ACCOUNTING MODEL — Subroutine TSMOD

1) Sum across size classes and regions to obtain vehicle sales by technology:

$$TECHNCS_{IT,T} = \sum_{OSC=1}^{6} \sum_{IR=1}^{9} NCSTECH_{IR,OSC,IT,T}$$

and: (B-119)

$$TECHNLT_{IT,T} = \sum_{OSC=1}^{6} \sum_{IR=1}^{9} NLTECH_{IR,OSC,IT,T}$$

where:

TECHNCS = Total new car sales, by technology
TECHNLT = Total new light truck sales, by technology
NCSTECH = New car sales, by region, size class, and technology, from the AFV Module
NLTECH = New light truck sales, by region, size class, and technology
OSC = Index of size class (1-6)
IR = Index of region (1-9)
IT = Index of vehicle technology (1-16)

2) These variables are assigned to the first vintages of the automobile and light truck stock arrays, and the population of subsequent vintages are calculated:

a) For *VINT* = 2-9:

$$PASSTK_{IT,VINT,T} = PASSTK_{IT,VINT-1,T-1} * SSURVP_{VINT-1}$$

and: (B-120)

$$LTSTK_{IT,VINT,T} = LTSTK_{IT,VINT-1,T-1} * SSURVLT_{VINT-1}$$

b) For $VINT$ = 10:

$$PASSTK_{IT,VINT=10,T} = \left(PASSTK_{IT,VINT=9,T-1} * SSURVP_{VINT=9}\right) + \left(PASSTK_{IT,VINT=10,T-1} * SSURVP_{VINT=10}\right)$$

and (B-121)

$$LTSTK_{IT,VINT=10,T} = \left(LTSTK_{IT,VINT=9,T-1} * SSURVLT_{VINT=10}\right) + \left(LTSTK_{IT,VINT=10,T-1} * SSURVLT_{VINT=10}\right)$$

where:

PASSTK = Surviving automobile stock, by technology and vintage
LTSTK = Surviving light truck stock, by technology and vintage
SSURVP = Fraction of a given vintage's automobiles which survive
SSURVLT = Fraction of a given vintage's light trucks which survive
$VINT$ = Index of vehicle vintage (1-10)

3) Add retired fleet vehicles to the appropriate vintage of the non-fleet population:

$$PASSTK_{IT,TVINT} = PASSTK_{IT,TVINT} + OLDFSTK_{VT=1,TYPE,ITECH,TVINT}$$

and: (B-122)

$$LTSTK_{IT,TVINT} = LTSTK_{IT,TVINT} + OLDFSTK_{VT=2,TYPE,ITECH,TVINT}$$

where:

OLTFSTK = Number of fleet vehicles rolled over into corresponding private categories
TVINT = Transition vintage: vintage at which vehicles of a given type are transferred
TYPE = Type of fleet vehicle: Business, Government, or Utility
ITECH = Index for the six fleet vehicle technologies: mapped to corresponding IT index

4) Sum over vintages and technologies to obtain total stocks of cars and light trucks:

$$STKCAR_T = \sum_{VINT=1}^{10} \sum_{IT=1}^{16} PASSTK_{IT,VINT,T}$$

and: (B-123)

$$STKTR_T = \sum_{VINT=1}^{10} \sum_{IT=1}^{16} LTSTK_{IT,VINT,T}$$

where:

STKCAR = Total stock of non-fleet automobiles in year T
STKTR = Total stock of non-fleet light trucks in year T

5) Calculate LDV shares of each technology:

$$VSPLDV_{IT,T} = \frac{\sum_{VINT=1}^{10} \left(PASSTK_{IT,VINT,T} + LTSTK_{IT,VINT,T}\right)}{STKCAR_T + STKTR_T} \qquad \textbf{(B-124)}$$

where:

VSPLDV = The light duty vehicle shares of each of the sixteen vehicle technologies

LIGHT DUTY VEHICLE STOCK ACCOUNTING MODEL — Subroutine TMPGSTK

1) Map non-gasoline vehicle sales from six to three size classes (IT = 1-15):

$$NCS3A_{IS,IT,T} = \sum_{OSC} \sum_{IR=1}^{9} NCSTECH_{IR,OSC,IT,T}$$

and **(B-125)**

$$NLT3A_{IS,IT,T} = \sum_{OSC} \sum_{IR=1}^{9} NLTECH_{IR,OSC,IT,T}$$

where:

NCS3A = New car sales by reduced size class and engine technology:
$IS = 1, OSC = 1,6;\ IS = 2, OSC = 2,3;\ IS = 3, OSC = 4,5$
NLT3A = New light truck sales by reduced size class and technolgy:
$IS = 1, OSC = 1,3;\ IS = 2, OSC = 2,5;\ IS = 3, OSC = 4,6$
NCSTECH = New car sales by region, technology, and six size classes
NLTECH = New light truck sales by region, technology, and six size classes

2) Calculate total regional sales of vehicles by reduced size class:

$$NCSR_{IR,IS,T} = \sum_{OSC} NCS_{IR,OSC,T}$$

and **(B-126)**

$$NLTSR_{IR,IS,T} = \sum_{OSC} NLTS_{IR,OSC,T}$$

where:

NCSR = Regional new car sales by reduced size class
NLTSR = Regional new light truck sales by reduced size class

3) Sum across regions:

$$NCS3SC_{IS,T} = \sum_{IR=1}^{9} NCSR_{IR,IS,T}$$

and (B-127)

$$NLTS3SC_{IS,T} = \sum_{IR=1}^{9} NLTSR_{IR,IS,T}$$

where:

NCS3SC = Total new car sales by reduced size class

NLTS3SC = Total new light truck sales by reduced size class

4) Sum conventional vehicle sales across regions:

$$NNCSCA_{OSC,T} = \sum_{IR=1}^{9} NCSTECH_{IR,OSC,IT=18,T}$$

and (B-128)

$$NNLTCA_{OSC,T} = \sum_{IR=1}^{9} NLTECH_{IR,OSC,IT=18,T}$$

where:

NNCSCA = New conventional car sales by six size classes

NNLTCA = New conventional light truck sales by six size classes

5) Calculate average MPG within reduced size classes:

$$AMPGC_{IS,T} = \sum_{OSC} \frac{NCMPG_{VT=1,OSC,T}}{2}$$

and (B-129)

$$AMPGT_{IS,T} = \sum_{OSC} \frac{NCMPG_{VT=2,OSC,T}}{2}$$

where:

AMPGC = Average new car MPG mapped from six to three size classes:

$IS = 1, OSC = 2,3;\ IS = 2, OSC = 1,6;\ IS = 3, OSC = 4,5$

AMPGT = Average new truck MPG mapped from six to three size classes:

$IS = 1, OSC = 1,3;\ IS = 2, OSC = 2,5;\ IS = 3, OSC = 4,6$

VT = Index of vehicle type: 1 = cars, 2 = light trucks

6) Calculate ratio of truck to car MPG by size class:

$$RATIO_{IS,T} = \frac{AMPGT_{IS,T}}{AMPGC_{IS,T}} \qquad \text{(B-130)}$$

where:

RATIO = Light truck MPG adjustment factor

7) Calculate the average efficiencies of the fifteen non-gasoline technologies:

$$MPGC_{IT,T} = \left[\frac{\sum_{IS=1}^{3} \frac{NCS3A_{IS,IT,T}}{NAMPG_{IT,IS,T}}}{\sum_{IS=1}^{3} NCS3A_{IS,IT,T}} \right]^{-1}$$

and: (B-131)

$$MPGT_{IT,T} = \left[\frac{\sum_{IS=1}^{3} \frac{NLT3A_{IS,IT,T}}{NAMPG_{IT,IS,T} * RATIO_{IS,T}}}{\sum_{IS=1}^{3} NLT3A_{IS,IT,T}} \right]^{-1}$$

where:

MPGC = New car fuel efficiency, by engine technology
MPGT = New light truck fuel efficiency, by engine technology
NAMPG = New AFV fuel efficiency, from the AFV model

8) Calculate new vehicle MPG for gasoline ICE's (*IT* = 16):

$$MPGC_{IT=16,T} = \left[\frac{\sum_{OSC=1}^{6} \frac{NNCSCA_{OSC,T}}{NCMPG_{OSC,T}}}{\sum_{OSC=1}^{6} NNCSCA_{OSC,T}} \right]^{-1}$$

and: (B-132)

$$MPGT_{IT=16,T} = \left[\frac{\sum_{OSC=1}^{6} \frac{NNLTCA_{OSC,T}}{NLTMPG_{OSC,T}}}{\sum_{OSC=1}^{6} NNLTCA_{OSC,T}} \right]^{-1}$$

where:

NCMPG = New car MPG, from the FEM model

NLTMPG = New light truck MPG, from the FEM model

9) Calculate average fuel efficiency across all technologies for cars and light trucks:

$$ANCMPG_T = \left[\sum_{IT=1}^{16} \frac{APSHRNC_{IT,T}}{MPGC_{IT,T}} \right]^{-1}$$

and:

$$ANTMPG_T = \left[\sum_{IT=1}^{16} \frac{APSHRNT_{IT,T}}{MPGT_{IT,T}} \right]^{-1} \qquad \text{(B-133)}$$

where:

ANCMPG = Average new car MPG

ANTMPG = Average new light truck MPG

APSHRNC = Absolute market share of new cars, by technology, from the AFV model

APSHRNT = Absolute market share of new light trucks, by technology, from the AFV model

10) Calculate total miles driven by each type of vehicle:

$$TOTMICT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} PASSTK_{IT,IV,T} * PVMT_{IV}$$

and:

$$TOTMITT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} LTSTK_{IT,IV,T} * LVMT_{IV} \qquad \text{(B-134)}$$

where:

TOTMICT = Total miles driven by cars

TOTMITT = Total miles driven by light trucks

PVMT = Average automobile VMT, by vintage, from RTECS

LVMT = Average light truck VMT, by vintage, from RTECS

11) Calculate total energy consumption:

$$CMPGT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} \frac{PASSTK_{IT,IV,T} * PVMT_{IV}}{CMPGSTK_{IT,IV,T} * VDF_{VT=1}}$$

and: (B-135)

$$TMPGT_T = \sum_{IT=1}^{16} \sum_{IV=1}^{10} \frac{LTSTK_{IT,IV,T} * LVMT_{IV}}{TTMPGSTK_{IT,IV,T} * VDF_{VT=2}}$$

where:

CMPGT = Automobile stock MPG
TMPGT = Light truck stock MPG
CMPGSTK = Automobile stock MPG, by vintage and technology
TTMPGSTK = Light truck stock MPG, by vintage and technology
VDF = Vehicle fuel efficiency degradation factor: VT = 1 for cars, VT = 2 for trucks

12) Calculate stock fuel efficiency:

$$SCMPG_T = \frac{TOTMICT_T}{CMPGT_T}$$

and: (B-136)

$$STMPG_T = \frac{TOTMITT_T}{TMPGT_T}$$

where:

SCMPG = Stock MPG for automobiles
STMPG = Stock MPG for light trucks

13) Calculate average fuel efficiency of light duty vehicles:

$$MPGFLT_T = \frac{TOTMICT_T + TOTMITT_T}{CMPGT_T + TMPGT_T} \quad \text{(B-137)}$$

where:

MPGFLT = Stock MPG for all light duty vehicles

14) Calculate average fuel efficiency by technology:

$$MPGTECH_{IT,N} = \frac{\sum_{IV=1}^{10} \frac{PASSTK_{IT,IV,T} * PVMT_{IV}}{CMPGSTK_{IT,IV,T} * VDF_{VT-4}} + \sum_{IV=1}^{10} \frac{LTSTK_{IT,IV,T} * LVMT_{IV}}{TTMPGSTK_{IT,IV,T} * VDF_{VT-2}}}{TOTMICT_T + TOTMITT_T} \quad \text{(B-138)}$$

where:

MPGTECH = Average stock MPG by technology

VEHICLE MILES TRAVELED MODEL — Subroutine TVMT

1) Calculate the cost of driving per mile:

$$COSTMI_T = \frac{TPMGTR_T * 0.125}{MPGFLT_T} \quad \text{(B-139)}$$

where:

COSTMI = Cost of driving per mile
TPMGTR = Price of motor gasoline
MPGFLT = Fuel economy of the automobile fleet
0.125 = Conversion factor for gasoline, in MMBtu/gallon

2) Calculate per capita income:

$$INCOME_T = \frac{TMC_YD_T}{TMC_POPAFO_T} \quad \text{(B-140)}$$

where:

INCOME = Per capita disposable personal income
TMC_YD = Total disposable personal income, from MACRO module
TMC_POPAFO = Total population, from MACRO module

3) Calculate unadjusted VMT per capita:

$$\begin{aligned} VMT16_T = {} & RHO \cdot VMTPC_{T-1} + ALPHA(1 - RHO) \\ & - BETAPE(COSTMI_T - RHO \cdot COSTMI_{T-1}) \\ & + BETAIE(INCOME_T - RHO \cdot INCOME_{T-1}) \\ & + BETADEM(PrFem_T - RHO \cdot PrFem_{T-1}) \end{aligned} \quad \text{(B-141)}$$

where:

VMT16 = Per capita VMT for persons 16 and older
ALPHA = Constant parameter for the VMT difference equation
BETAPE = Parameter associated with the cost of driving
BETAIE = Parameter associated with disposable persoal income
BETADEM = Parameter associated with demographic influences
PrFem = Ratio of per capita female driving to per capita male driving.
RHO = Lag factor, estimated using the Cochrane-Orcutt iterative procedure to be 0.72.

4) Calculate adjusted VMT per capita:

$$ADJVMTPC_T = VMT16_T \cdot DAF_T \quad \text{(B-142)}$$

where:

ADJVMTPC = Demographically-adjusted per capita VMT
DAF = Demographic adjustment factor

5) Calculate total VMT:

$$VMTLDV_T = ADJVMTPC_T * TMC_POP16_T \quad \text{(B-143)}$$

where:

VMTLDV = Total VMT for light duty vehicles

6) Calculate net VMT, subtracting off fleet and light truck freight VMT:

$$VMTEE_T = VMTLDV_T - (FLTVMT_T + FVMTSC_{ld-1,T}) \quad \text{(B-144)}$$

where:

VMTEE = VMT for personal travel
FLTVMT = Fleet VMT
FVMTSC = Freight VMT by size class

7) Calculate VMT by technology:

$$VMTECH_{IT,T} = VMTEE_T * VSPLDV_{IT,T} \quad \text{(B-145)}$$

where:

VMTECH = Personal travel VMT by technology
VSPLDV = Sales shares of vehicles by technology

8) Calculate fractional change of VMT:

$$XLDVMT_T = \frac{VMTEE_T}{VMTEE_{T-4}} \quad \text{(B-146)}$$

where:

XLDVMT = Fractional change of VMT over base year (1990)

VEHICLE MILES TRAVELED MODEL — Subroutine TFREISMOD

1) Calculate light truck sales dedicated to freight:

$$TRSAL_T = 0.408427 * TMC_SQDTRUCKSL_T \quad \text{(B-147)}$$

where:

TRSAL = Light truck sales for freight
TMC_SQDTRUCKSL = Total light truck sales, from MACRO module

2) Calculate sales by technology:

$$TRSALTECH_{IT,T} = TRSAL_T * FLVMTSHR_{IS-4,IT,T} \quad \text{(B-148)}$$

where:

TRSALTECH = Light truck sales by technology
FLVMTSHR = VMT-weighted shares by size class and technology

3) Add to vintage array and adjust stock survival:

$$TRSTKTECH_{IT,IV=1,T} = TRSALTECH_{IT,T}$$

$$TRSTKTECH_{IT,IV,T} = TRSTKTECH_{IT,IV-1,T-1} * SSURVLT_{IV-1} \quad ; \quad IV = 2-9$$

and

$$TRSTKTECH_{IT,IV=10,T} = \left(TRSTKTECH_{IT,IV=9,T-1} * SSURVLT_{IV=9}\right) + \left(TRSTKTECH_{IT,IV=10,T-1} * SSURVLT_{IV=10}\right) \quad \text{(B-149)}$$

where:

TRSTKTECH = Light truck stock by technology

SSURVLT = Array of survival rates for light trucks

4) Sum over vintages:

$$TRSTKTOT_{IT,T} = \sum_{IV=1}^{10} TRSTKTECH_{IT,IV,T} \quad \text{(B-150)}$$

where:

TRSTKTOT = Total light truck stock by technology

5) Sum over technologies:

$$TRSTK_{T} = \sum_{IT=1}^{5} TRSTKTOT_{IT,T} \quad \text{(B-151)}$$

where:

TRSTK = Total light truck stock

6) Calculate average MPG for light trucks:

$$TRFLTMPG_{T} = \left[\frac{\sum_{IT=1}^{5}\left(\frac{TRSTKTOT_{IT,T}}{FMPG_{IS=1,IT,T}}\right)}{\sum_{IT=1}^{5} TRSTKTOT_{IT,T}}\right]^{-1} \quad \text{(B-152)}$$

where:

TRFLTMPG = Average light truck MPG

This subroutine calculates aggregate fuel efficiencies for cars and light trucks.

1) Sum fleet vehicle sales over size class:

$$FLTECHSALT_{VT,ITY,ITECH,T} = \sum_{IS=1}^{3} FLTECHSAL_{VT,ITY,IS,ITECH,T} \quad \text{(B-153)}$$

where:

FLTECHSALT = Vehicle purchases by fleet type and technolgy
FLTECHSAL = Fleet sales by size, technology, and fleet type
VT = Index of vehicle type: 1 = cars, 2 = light trucks
ITECH = Index of engine technology (1-6)
ITY = Index of fleet type: Business, Government, Utility
IS = Index of size class (1-3)

2) Calculate new vehicle MPG:

$$FLTMPGNEW_{VT,ITECH,T} = \left[\frac{\sum_{ITY=1}^{3} \frac{FLTECHSALT_{VT,ITY,ITECH,T}}{FLTMPG_{VT,ITY,ITECH,T}}}{\sum_{ITY=1}^{3} FLTECHSALT_{VT,ITY,ITECH,T}} \right]^{-1} \quad \text{(B-154)}$$

where:

FLTMPGNEW = New fleet vehicle MPG by vehicle type and technology
FLTMPG = Fleet vehicle MPG by vehicle type, size class, and technology

3) Sum fleet stock across fleet types:

$$FLTSTOCK_{VT,ITECH,T} = \sum_{ITY=1}^{3} FLTECHSTK_{VT,ITY,ITECH,T} \quad \text{(B-155)}$$

where:

FLTSTOCK = Total fleet vehicle stock, by technology
FLTECHSTK = Total fleet vehicle stock, by technology and fleet type

4) Calculate average MPG of fleet and non-fleet vehicles, by technology:

a) For cars:

$$CCMPGLDV_{IT,T} = \left[\frac{\left(\frac{TECHNCS_{IT,T}}{MPGC_{IT,T}} \right) + \left(\frac{FLTSTOCK_{VT-1,ITECH,T}}{FLTMPGNEW_{VT-1,ITECH,T}} \right)}{TECHNCS_{IT,T} + FLTSTOCK_{VT-1,ITECH,T}} \right]^{-1} \quad \text{(B-156)}$$

where:

CCMPGLDV = New car MPG, by technology *IT*
IT = Index of vehicle technology (1-16)
ITECH = Index of fleet vehicle technologies which correspond to the *IT* index
TECHNCS = Non-fleet new car sales, by technology *IT*
MPGC = New car MPG, by technology *IT*
FLTSTOCK = New fleet stock, by vehicle type and technology *ITECH*
FLTMPGNEW = New fleet vehicle MPG, by vehicle type and technology *ITECH*

b) For light trucks:

$$TTMPGLDV_{IT,T} = \left[\frac{\left(\frac{TECHNLT_{IT,T}}{MPGT_{IT,T}} \right) + \left(\frac{FLTSTOCK_{VT-2,ITECH,T}}{FLTMPGNEW_{VT-2,ITECH,T}} \right)}{TECHNLT_{IT,T} + FLTSTOCK_{VT-2,ITECH,T}} \right]^{-1} \quad \text{(B-157)}$$

where:

TTMPGLDV = New light truck MPG, by technology *IT*
TECHNLT = Non-fleet new light truck sales, by technology *IT*
MPGT = New light truck MPG, by technology *IT*

5) Calculate total stock by vehicle type and technology:

$$STOCKLDV_{VT,IT2,T} = STKCT_{VT,IT,T} + FLTSTOCK_{VT,ITECH,T} \quad \text{(B-158)}$$

where:

STOCKLDV = Total stock of fleet and non-fleet vehicles, by technology
STKCT = Stock of non-fleet vehicles, by technology
IT = Index of vehicle technology (1-16)
IT2 = Reassigned indices of vehicle technology *IT2* = 1-16; *IT* = 16,15,1-14
ITECH = Index of fleet technologies which map to corresponding *IT* and *IT2* as follows:
IT2 = 1,3,5,7,8,9; *IT* = 16,1,3,5,6,7; *ITECH* = 6,1,2,3,4,5

6) Calculate total stock across technologies:

$$TSTOCKLDV_{VT,T} = \sum_{IT2=1}^{10} STOCKLDV_{VT,IT2,T} \qquad \text{(B-159)}$$

where:

TSTOCKLDV = Total stock by vehicle type *VT*

7) Calculate average MPG of cars and light trucks:

$$TMPGLDVSTK_{VT=1,T} = \left[\frac{\sum_{IT2=1}^{10} \left(\frac{STOCKLDV_{VT=1,IT2,T}}{CCMPGLDV_{IT2,T}} \right)}{\sum_{IT2=1}^{10} STOCKLDV_{VT=1,IT2,T}} \right]^{-1}$$

and (B-160)

$$TMPGLDVSTK_{VT=2,T} = \left[\frac{\sum_{IT2=1}^{10} \left(\frac{STOCKLDV_{VT=2,IT2,T}}{TTMPGLDV_{IT2,T}} \right)}{\sum_{IT2=1}^{10} STOCKLDV_{VT=2,IT2,T}} \right]^{-1}$$

where:

TMPGLDVSTK = Average MPG by vehicle type *VT*

8) Calculate overall average MPG of light-duty veh : fleet:

$$TLDVMPG_T = \left[\frac{\sum_{VT=1}^{2} \left(\frac{TSTOCKLDV_{VT,T}}{TMPGLDVSTK_{VT,T}} \right)}{\sum_{VT=1}^{2} TSTOCKLDV_{VT,T}} \right]^{-1} \qquad \text{(B-161)}$$

where:

TLDVMPG = Average fuel economy of light-duty vehicles

HIGHWAY FREIGHT MODEL Subroutine TFREI

1) Calculate freight transport demand by trucks for manufacturing, agriculture and mining industries (I = 1-10):

$$FTMT_{I,T} = FTMT_{I,T_0} \cdot FAC_{I,Mode} \cdot \left[\frac{TSIC_{I,T}}{TSIC_{I,T_0}}\right] \quad \text{(B-162)}$$

where:

$FTMT_{I,T}$ = Total freight traffic (Ton-Miles) for a given industry, I, in year T
TSIC = Value of output of industry I, in base year (1990) dollars
$FAC_{I,Mode}$ = A freight adjustment coefficient
Mode = Index of freight mode: Truck, Rail, Marine

2) Convert ton-miles to vehicle miles:

$$FVMT_{I,T} = \frac{FTMT_{I,T}}{FRLOAD_I} \quad \text{(B-163)}$$

where:

FVMT = Freight vehicle-miles traveled
FRLOAD = Constant relating a given industry's ratio of ton-miles to vehicle-miles

3) Sum across industries:

$$FFVMT_{IX=1,T} = \sum_{I=1}^{10} FVMT_{I,T} \quad \text{(B-164)}$$

where:

FFVMT = Total freight truck vehicle-miles traveled in industry group IX
IX = Place holder for industry group

4) Estimate travel demand for construction and retail industries (I = 11, 12; IX = 2, 3):

$$FFVMT_{IX=2,T} = INTVMT90_{I=11} * \frac{TSIC_{I=11,T}}{TSIC90}$$

and (B-165)

$$FFVMT_{IX=3,T} = INTVMT90_{I=12} * \frac{TMC_YD_T}{TYD8290}$$

where:

INTVMT90 = Base year (1990) travel demand for the considered industries
TSIC90 = Base year value of industrial output
TMC_YD = Disposable personal income, from the MACRO module
TYD8290 = Base year disposable personal income

5) Calculate total VMT for freight:

$$FTOTVMT_T = \sum_{IX=2}^{3} FFVMT_{IX,T} \quad \text{(B-166)}$$

where:

FTOTVMT = Total VMT demand for trucks

6) Calculate growth in VMT:

$$XTOTVMT_T = \frac{FTOTVMT_T}{FTOTVMT_1} \quad \text{(B-167)}$$

where:

XTOTVMT = Fractional growth in freight VMT over base year

7) Distribute freight VMT among three size classes:

$$FVMTSC_{IS,T} = FTOTVMT_T * FBENCH * TRSCSHR_{IS,N} \quad \text{(B-168)}$$

where:

FVMTSC = Freight VMT by size class
FBENCH = Benchmarking factor to ensure congruence with 1990 data
TRSCSHR = Travel share distribution factors, held constant
IS = Index of truck size class (1-3)

8) Distribute freight VMT among fuel technologies:

a) Calculate share growth adjustments:

$$FSHR_{IS,TECH,T} = FLVMTSHR_{IS,TECH,T-1} * GROWTH_{IS,TECH} \quad \text{(B-169)}$$

where:

FSHR = Adjusted technology share of VMT demand
FLVMTSHR = Normalized technology share of VMT demand
GROWTH = Constant growth adjustment factor for each technology and size class:
GROWTH = 1.0 when *TECH* = 3,4,5
TECH = Index of engine technology (1-5)

b) Reassign variables for *TECH* = 3-5:

$$FLVMTSHR_{IS,TECH,T} = FSHR_{IS,TECH,T} \quad ; \quad TECH = 3,4,5 \quad \text{(B-170)}$$

c) Normalize and reassign shares for *TECH* = 1,2:

$$FLVMTSHR_{IS,TECH,T} = \left(\frac{FSHR_{IS,TECH,T}}{\sum_{TECH=1}^{2} FSHR_{IS,TECH,T}} \right) * \left(1 - \sum_{TECH=6}^{5} FSHR_{IS,TECH,T} \right) \quad \text{(B-171)}$$

d) Calculate VMT by technology:

$$FVMTECHSC_{IS,TECH,T} = FVMTSC_{IS,T} * FLVMTSHR_{IS,TECH,T} \quad \text{(B-172)}$$

where:

FVMTECHSC = Freight truck VMT by size class and technology

9) Sum VMT across technologies for second size class for use in subroutine TMISC:

$$SUMFVMT_{T} = \sum_{TECH=1}^{5} FVMTECHSC_{IS=2,IT,T} \quad \text{(B-173)}$$

where:

SUMFVMT = Total freight VMT for the second size class

10) Calculate freight truck MPG:

$$FMPG_{IS,TECH,T} = FMPG_{IS,TECH,T-1} * (1 + TBETA1_{IS}) * \left(MAX \left\{ 1.0 , \left[\frac{TPMGTR_T}{TPMGTR_{T-1}} \right] \right\} \right)^{TBETA2_{IS}} \quad \text{(B-174)}$$

where:

FMPG = Freight truck MPG, by size class and technology
TPMGTR = Price of motor gasoline
TBETA1 = Base rate of fuel economy growth, by size class
TBETA2 = Fuel-price sensitive rate of fuel economy growth, by size class

11) Calculate fractional improvement of fuel economy for gasoline-fueled light trucks:

$$XFREFF_T = \frac{FMPG_{IS=4,TECH=4,T}}{FMPG_{IS=4,TECH=4,T=1}} \quad \text{(B-175)}$$

where:

XFREFF = Fuel economy improvement over base year

12) Calculate fuel consumption for each truck type:

$$FFD_{IS,TECH,T} = \left(\frac{FVMTECHSC_{IS,TECH,T}}{FMPG_{IS,TECH,T}} \right) * QBTU_{TECH} \quad \text{(B-176)}$$

where:

FFD = Freight fuel demand, in MMBtu
QBTU = Heat content of fuel used by the considered technology, in MMBtu/gallon

13) Calculate average fuel efficiency for second size class, for use in subroutine TMISC:

$$FFMPG_T = \sum_{TECH=4}^{5} \frac{FMPG_{IS=2,TECH,T}}{5} \quad \text{(B-177)}$$

where:

FFMPG = Average truck fuel economy for seconc size class

14) Calculate total fuel demand for trucks, by technology:

where:

$$FFDT_{TECH,T} = \sum_{IS=1}^{3} FFD_{IS,TECH,T} \quad \text{(B-178)}$$

FFDT = Total fuel demand, by technology, in MMBtu

15) Calculate regional consumption:

$$TQFREIR_{TECH,IR,T} = FDT_{TECH,T} * SEDSHR_{FUEL,IR,T}$$

$$\text{and} \quad \text{(B-179)}$$

$$TQFREIRSC_{IS,TECH,IR,T} = FFD_{IS,TECH,T} * SEDSHR_{FUEL,IR,T}$$

where:

TQFREIR = Total regional freight energy demand by technology
TQFREIRSC = Total regional freight energy demand by technology and size class
SEDSHR = Regional shares of fuel consumption, from SEDS

RAIL FREIGHT MODEL — Subroutine TRAIL

1) Calcutate ton-miles traveled for rail, by industry:

$$RTMT_{I,T} = RTMT_{I,T_0} \cdot FAC_{I,MODE} \cdot \left[\frac{TSIC_{I,T}}{TSIC_{I,T_0}}\right] \quad \text{(B-180)}$$

where:

RTMT = Rail ton-miles traveled, by industry *I*
MODE = Index of freight mode: truck, rail, marine
TSIC = Value of industrial output, by industry
I = Index of NEMS industrial category
FAC = Freight adjustment coefficient, by industry and mode

2) Sum across industries:

$$RTMTT_T = \sum_{I=1}^{10} RTMT_{I,T} \quad \text{(B-181)}$$

where:

RTMTT = Total rail ton-miles traveled

3) Estimate energy consumption by rail:

$$TQRAILT_T = FERAIL_T \cdot RTMTT_T \quad \text{(B-182)}$$

where:

TQRAILT = Total energy demand by rail

FERAIL = Rail efficiency coefficient, in Btu/ton-mile

4) Increment rail demand for specific fuels:

$$TQRAIL_{IF,T} = TQRAIL_{IF,T-1} \cdot \left(\frac{TQRAILT_T}{TQRAILT_{T-1}} \right) \quad \text{(B-183)}$$

where:

TQRAIL = Rail demand, by fuel *IF*

IF = Index of fuel type

5) Divide into regions:

$$TQRAILR_{IF,IR,T} = TQRAIL_{IF,T} * SEDSHR_{IF,IR,T} \quad \text{(B-184)}$$

where:

TQRAILR = Regional demand by fuel type

SEDSHR = Regional shares of fuel demand, from SEDS

IR = Index of census region (1-9)

6) Calculate fractional change in rail travel and fuel efficiency:

$$XRAIL_T = \frac{RTMTT_T}{RTMTT_{T-1}}$$

and (B-185)

$$XRAILEFF_T = \frac{FERAIL_{T-1}}{FERAIL_T}$$

where:

XRAIL = Growth in rail travel from base year
XRAILEFF = Growth in rail efficiency from base year

WATERBORNE FREIGHT MODEL — Subroutine TSHIP

1) Calcutate ton-miles traveled for domestic shipping, by industry:

$$STMT_{I,T} = STMT_{I,T_0} \cdot FAC_{I,MODE} \cdot \left[\frac{TSIC_{I,T}}{TSIC_{I,T_0}}\right] \quad \text{(B-186)}$$

where:

STMT = Ship ton-miles traveled, by industry *I*

2) Sum across industries:

$$STMTT_T = \sum_{I=1}^{10} STMT_{I,T} \quad \text{(B-187)}$$

where:

STMTT = Total ship ton-miles traveled

3) Estimate energy consumption by ship:

$$SFDT_T = FESHIP_T \cdot STMTT_T \cdot SFDBENCH \quad \text{(B-188)}$$

where:

SFDT = Total energy demand by ship
FESHIP = Ship efficiency coefficient, in Btu/ton-mile
SFDBENCH = Benchmark factor to ensure congruence with 1990 data

4) Allocate energy demand among specific fuels:

$$SFD_{IF,T} = SFDT_T \cdot SFSHARE_{IF} \quad \text{(B-189)}$$

where:

SFD = Domestic ship energy demand, by fuel *IF*

SFSHARE = Constant allocation share for domestic shipping, by fuel

5) Divide into regions:

$$TQSHIPR_{IF,IR,T} = SFD_{IF,T} * SEDSHR_{IF,IR,T} \quad \text{(B-190)}$$

where:

TQSHIPR = Regional ship demand by fuel type

SEDSHR = Regional shares of fuel demand, from SEDS

6) Calculate international shipping fuel demand:

$$ISFDT_T = ISFDT_{T-1} + \left[\frac{GROSST_T}{GROSST_{T-1}} - 1 \right] * 0.5 * ISFDT_{T-1} \quad \text{(B-191)}$$

where:

ISFDT = Total international shipping fuel demand

GROSST = Value of gross trade (imports + exports)

7) Allocate among the considered fuels:

$$ISFD_{IF,T} = ISFDT_T \cdot ISFSHARE_{IF} \quad \text{(B-192)}$$

where:

ISFD = International ship energy demand, by fuel *IF*

ISFSAHRE = Constant allocation share for international shipping, by fuel

8) Divide into regions:

$$TQISHIPR_{IF,IR,T} = ISFD_{IF,T} * SEDSHR_{IF,IR,T} \quad \text{(B-193)}$$

where:

TQISHIPR = Regional international shipping demand by fuel type

9) Calculate fractional change in domestic ship travel and fuel efficiency:

$$XSHIP_T = \frac{STMTT_T}{STMTT_{T-1}}$$

and (B-194)

$$XSHIPEFF_T = \frac{FESHIP_T}{FESHIP_{T-1}}$$

where:

XSHIP = Growth in ship travel from base year

XSHIPEFF = Growth in ship efficiency from base year

AIR TRAVEL DEMAND MODEL — Subroutine TAIRT

1) Calculate the cost of flying:

$$YIELD_T = 4.22 + .94\,TPJFTR_T + 65.42\,OPCST_T \qquad \text{(B-195)}$$

where:

YIELD = Cost of air travel, expressed in cents per RPM
TPJFTR = Price of jet fuel, in dollars per million Btu
OPCST = Non-fuel operating costs, in dollars per available seat-mile

2) Calculate the revenue passenger-miles per capita for each type of travel:

a) For business travel:

$$RPMBPC_T = -126.8 + .050\left(\frac{TMC_GDP_T}{TMC_POPAFO_T}\right) - 12.80\,YIELD_T \qquad \text{(B-196)}$$

b) For personal travel:

$$RPMPPC_T = -587.8 + .118\left(\frac{TMC_YD_T}{TMC_POPAFO_T}\right) - 20.56\,YIELD_T \qquad \text{(B-197)}$$

c) For international travel:

$$RPMIPC_T = PCTINT_T \cdot (RPMBPC_T + RPMPPC_T) \qquad \text{(B-198)}$$

where:

RPMBPC = Per capita revenue passenger miles for business travel
RPMPPC = Per capita revenue passenger miles for personal travel
RPMIPC = Per capita revenue passenger miles for international travel
TMC_GDP = Gross domestic product, from MACRO module
TMC_YD = Disposable personal income, from MACRO module
TMC_POPAFO = Total domestic population, from MACRO module
PCTINT = Proportionality factor relating international to domestic travel levels

3) Calculate the revenue ton-miles (RTM) of air freight:

$$RTM_T = (-18{,}165.6 + 22.35\,TMC_EXDN87_T + 5.77\,TMC_GDP_T) \cdot DFRT_T \qquad \text{(B-199)}$$

where:

TMC_EXDN87 = Value of merchandise exports, from MACRO module

DFRT = Fraction of freight ton-miles transported by dedicated carriers

4) Calculate total revenue passenger-miles flown for each category of travel:

a) For business travel:

$$RPMB_T = RPMBPC_T \cdot TMC_POPAFO_T \qquad \text{(B-200)}$$

b) For personal travel:

$$RPMP_T = RPMPPC_T \cdot TMC_POPAFO_T \cdot DI_T \qquad \text{(B-201)}$$

c) For international travel:

$$RPMI_T = RPMIPC_T \cdot TMC_POPAFO_T \qquad \text{(B-202)}$$

where:

RPMB = Revenue passenger miles for business travel

RPMP = Revenue passenger miles for personal travel

RPMI = Revenue passenger miles for international travel

DI = Demographic adjustment index, reflecting the public's propensity to fly

5) Calculate total domestic air travel:

$$RPMD_T = RPMB_T + RPMP_T \qquad \text{(B-203)}$$

where:

RPMD = Total domestic air travel

6) Calculate the total demand for available seat-miles:

$$ASMDEMD_T = \left(\frac{RPMD_T}{LFDOM_T}\right) + \left(\frac{RPMI_T}{2 * LFINTER_T}\right) + (RTM_T \cdot EQSM) \qquad \text{(B-204)}$$

where:

ASMDEMD = Total demand for available seat-miles
LFDOM = Load factor for domestic travel
LFINTER = Load factor for international travel
EQSM = Equivalent seat-miles conversion factor; used to transform freight RTM's

AIRCRAFT FLEET EFFICIENCY MODEL — Subroutine TAIREFF

1) Calculate available seat-miles per plane, by aircraft type:

$$ASMP_{IT,T} = AIRHRS_{IT,T} * AVSPD_{IT,T} * SEAT_{IT,T} \qquad \text{(B-205)}$$

where:

ASMP = The available seat-miles per plane, by type.
AIRHRS = The average number of airborne hours per aircraft.
AVSPD = The average flight speed.
SEAT = The average number of seats per aircraft.
IT = Index of aircraft type: 1 = narrow body, 2 = wide body

2) Calculate fraction of seat-mile demand accomodated by narrow-body aircraft:

$$SMFRACN_T = \left[\left(\frac{ASMDEMD_{IT=1,T-1}}{SMDEMD_{T-1}}\right) + DELTA \cdot \left(\frac{ASMDEMD_{IT=2,T-1}}{SMDEMD_{T-1}}\right)\right] \; ; \; DELTA \geq 0$$

$$= \left[\left(\frac{ASMDEMD_{IT=1,T-1}}{SMDEMD_{T-1}}\right) \cdot (1 + DELTA)\right] \; ; \; DELTA < 0 \qquad \text{(B-206)}$$

where:

SMFRACN = Fraction of seat-mile demand on narrow-body planes
ASMDEMD = Demand for available seat-miles, by aircraft type
DELTA = User-specified rate of passenger shifts between aircraft types

3) Calculate current seat-miles demanded by aircraft type:

$$ASMDEMD_{IT=1,T} = SMDEMD_T * SMFRACN_T$$

and (B-207)

$$ASDEMD_{IT=2,T} = SMDEMD_T * (1.0 - SMFRACN_T)$$

4) Calculate survival rates of aircraft:

$$SURVPCT_{IVINT} = \left[1 + EXP\left(SURVK * (T50 - IVINT)\right)\right]^{-1}$$

and (B-208)

$$SSURVPCT_{IVINT} = \frac{SURVPCT_{IVINT}}{SURVPCT_{IVINT-1}}$$

where:

SURVPCT = Survival rate of planes of a given vintage *IVINT*
SSURVPCT = Marginal survival rate of planes of a given vintage
IVINT = Index of aircraft vintage
SURVK = User-specified proportionality constant
T50 = User-specified vintage at which stock survival is 50%

5) Calculate surviving seat-miles from previous year:

$$SMSURV_{IT,T} = \sum_{IVINT=2}^{60} NPCHSE_{IT,IVINT-1,T-1} * SSURVPCT_{IVINT} * ASMP_{IT,T} \quad \text{(B-209)}$$

where:

SMSURV = Surviving available seat-miles, by aircraft type
NPCHSE = Surviving aircraft stock, by vintage and aircraft type

6) Calculate new aircraft purchases:

$$NPCHSE_{IT,IVINT=1,T} = \left[\frac{ASMDEMD_{IT,T} - SMSURV_{IT,T}}{ASMP_{IT,T}}\right] \quad \text{(B-210)}$$

7) Adjust array of aircraft stocks by vintage:

$$NPCHSE_{IT,IVINT,T} = NPCHSE_{IT,IVINT-1,T-1} * SSURVPCT_{IVINT} \quad ; \quad IVINT = 2 - 60 \qquad \text{(B-211)}$$

8) Calculate aircraft stock across vintages:

$$NSURV_{IT,T} = \sum_{IVINT=1}^{60} NPCHSE_{IT,IVINT,T} \qquad \text{(B-212)}$$

where:

NSURV = Number of surviving aircraft, by type

9) Calculate fraction of current year stock which is old (*IVINT* > 1):

$$STKOLD_{IT,T} = \frac{\left(NSURV_{IT,T} - NPCHSE_{IT,IVINT-1,T}\right)}{NSURV_{IT,T}} \qquad \text{(B-213)}$$

where:

STKOLD = Fraction of planes older than one year, by aircraft type

10) Calculate effect of technology improvements:

a) Calculate time effect:

$$TIMEFX_{IFX,T} = TIMEFX_{IFX,T-1} + \left(TIMECONST * TPN_{IFX} * TYRN_{IFX}\right) \qquad \text{(B-214)}$$

where:

TIMEFX = Factor reflecting the length of time an aircraft technology improvement has been commercially viable

IFX = Index of technology improvements (1-6)

TIMECONST = User-specified scaling constant, reflecting the importance of the passage of time

TPN = Binary variable (0,1) which tests whether current fuel price exceeds the considered techology's trigger price

TYRN = Binary variable which tests whether current year exceeds the considered technology's year of introduction

b) Calculate the cost effect:

$$COSTFX_{IFX,T} = 10 * \left(\frac{TPJFGAL_T - TRAGPRICE_{IFX}}{TPJFGAL_T} \right) * TPN_{IFX} * TYRN_{IFX} * TPZ_{IFX} \quad \text{(B-215)}$$

where:

COSTFX = Factor reflecting the magnitude of the difference between the price of jet fuel and the trigger price of the considered technology

TPJFGAL = Price of jet fuel

TRIGPRICE = Price of jet fuel above which the considered technology is assumed to be commercially viable

TPZ = Binary variable which tests whether implementation of the considered technology is dependent on fuel price

c) Calculate the total effect:

$$TOTALFX_{IFX,T} = TIMEFX_{IFX,T} + COSTFX_{IFX,T} - BASECONST \quad \text{(B-216)}$$

where:

TOTALFX = Overall effect of fuel price and time on implementation of technology *IFX*

BASECONST = Baseline constant, used to anchor the technology penetration curve

d) Calculate the penetration of new technologies:

$$TECHFRAC_{IFX,T} = \left[1 + EXP\left(-TOTALFX_{IFX,T} \right) \right]^{-1} \quad \text{(B-217)}$$

where:

TECHFRAC = Fration of new aircraft purchases which incorporate a given technology

11) Calculate fractional fuel efficiency improvement for new aircraft, by type:

$$FRACIMP_{IT<4,T} = 1.0 + EFFIMP_{IFX<4} * \left(TECHFRAC_{IFX<4,T} - TECHFRAC_{IFX<4,T} \right) + \sum_{IFX<4}^{8} EFFIMP_{IFX} * TECHFRAC_{IFX,T}$$

and

$$FRACIMP_{IT<2,T} = 1.0 + \sum_{IFX<4}^{8} EFFIMP_{IFX} * TECHFRAC_{IFX,T} \quad ; \quad IFX \neq 2 \quad \text{(B-218)}$$

where:

FRACIMP = Fractional improvement over base year (1990) fuel efficiency, by type

EFFIMP = Fractional improvement associated with a given technology

12) Ensure that technical improvements provide at least as much efficiency gain as average growth in remainder of air fleet:

$$NEWSMPG_{IT,T} = MAX\left[(FRACIMP_{IT,T} * SMPG_{IT,T-1}),\ ((1.0 + P_{IT,T}) * SMPGIT,T-1 * 1.05)\right] \quad \text{(B-219)}$$

where:

NEWSMPG = Average seat-miles per gallon of new aircraft purchases
SMPG = Surviving fleet average seat-miles per gallon, by aircraft type
RHO = Average historic rate of growth of fuel efficiency

13) Calculate average fuel economy of aircraft fleet, by type:

$$SMPG_{IT,T} = \left[\left(\frac{STKOLD_{IT,T}}{(1 + RHO_{IT}) \cdot (SMPG_{IT,T-1})}\right) + \left(\frac{1 - STKOLD_{IT,T}}{NEWSMPG_{IT,T}}\right)\right]^{-1} \quad \text{(B-220)}$$

14) Calculate average fuel economy of aircraft fleet:

$$SMPGT_{T} = \left[\left(\frac{SMFRACN_{T}}{SMPG_{IT-1,T}}\right) + \left(\frac{(1 - SMFRACN_{T})}{SMPG_{IT-2,T}}\right)\right]^{-1} \quad \text{(B-221)}$$

where:

SMPGT = Overall fleet average seat-miles per gallon

15) Calculate demand for jet fuel, incrementing by 5% to reflect consumption by private aircraft:

$$JFGAL_{T} = \left(\frac{SMDEMD_{T}}{SMPGT_{T}}\right) * 1.05 \quad \text{(B-222)}$$

where:

JFGAL = Consumption of jet fuel, in gallons

16) Calculate demand for aviation gasoline:

$$AGD_T = BASEAGD + GAMMA * EXP\left[-KAPPA * (IYEAR - 1979)\right] \quad \text{(B-223)}$$

where:

AGD = Demand for aviation gasoline, in gallons
BASEAGD = Baseline demand for aviation gasoline
GAMMA = Baseline adjustment factor
KAPPA = Exogenously-specified decay constant
IYEAR = Current year

17) Convert from gallons to Btu:

$$JFBTU_T = JFGAL_T * \left(\frac{5.670\ MMBtu/bbl}{42\ gal/bbl}\right)$$

and

$$AGDBTU_T = AGD_T * \left(\frac{5.048\ MMBtu/bbl}{42\ gal/bbl}\right) \quad \text{(B-224)}$$

where:

JFBTU = Jet fuel demand, in Btu
AGDBTU = Aviation gasoline demand, in Btu

18) Regionalize demand:

$$QJETR_{IR,T} = JFBTU_T * SEDSHR_{IF,IR,T}$$

and

$$QAGR_{IR,T} = QAGDBTU_T * SEDSHR_{IF,IR,T} \quad \text{(B-225)}$$

where:

QJETR = Regional demand for jet fuel
QAGR = Regional demand for aviation gasoline
SEDSHR = Regional shares of fuel demand, from SEDS

19) Calculate fractional changes in air travel and aircraft efficiency:

$$XAIR_T = \frac{SMDEMD_T}{SMDEMD_{T-1}}$$

and (B-226)

$$XAIREFF_T = \frac{SMPGT_T}{SMPGT_{T-1}}$$

where:

XAIR = Fractional change in air travel from base year

XAIREFF = Fractional change in aircraft fuel efficiency from base year

MILITARY DEMAND MODEL

Subroutine TMISC

Calculate military energy use:

1) Calculate growth in military budget:

$$MILTARGR_T = \frac{TMC_GRML87_T}{TMC_GFML87_{T-1}} \quad \text{(B-227)}$$

where:

MILTARGR = Fractional growth of military budget
TMC_GRML87 = Military budget, from MACRO module

2) Calculate fuel demand:

$$MFD_{IF,T} = MFD_{IF,T-1} * MILTARGR_T \quad \text{(B-228)}$$

where:

MFD = Demand for fuel by military
IF = Index of fuel type

3) Regionalize demand:

$$QMILTR_{IF,IR,T} = MFD_{IF,T} * MILTRSHR_{IF,IR,T} \quad \text{(B-229)}$$

where:

QMILTR = Regional military demand for fuel
MILTRSHR = Regional shares of military demand for fuel

Calculate mass-transit consumption:

1) Calculate passenger-miles by mode:

$$TMOD_{IM-1,T} = VMTEE_T * TMLOAD89_{IM-1}$$

and:

$$TMOD_{IM,T} = TMOD_{IM,T-1} * \left[\frac{TMOD_{1,T}}{TMOD_{1,T-1}}\right]^{BETAMS} \quad \text{(B-230)}$$

where:

TMOD = Passenger-miles traveled, by mode
VMTEE = LDV vehicle-miles traveled, from the VMT module
TMLOAD89 = Average passengers per vehicle, by mode (1=LDV's)
BETAMS = Coefficient of proportionality, relating mass transit to LDV travel
IM = Index of transportation mode: 1 = LDV's, 2-4 = Buses, 5-7 = Rail

2) Calculate mass transit efficiencies, in Btu per passenger-mile:

$$TMEFFL_{IM,T} = \frac{\left[TMEFF89_{IM} * \left(\frac{FMPG_{TYPE,T}}{FMPG89_{TYPE}}\right)\right]}{TMLOAD89_{IM}} \quad \text{(B-231)}$$

where:

TMEFFL = Btu per passenger-mile, by mass transit mode
TMEFF89 = Base-year Btu per vehicle-mile, by mode
FMPG = Fuel efficiency, by vehicle type, from the Freight Module
FMPG89 = Base-year fuel efficiency, by vehicle type, from the Freight Module
TYPE = Vehicle type, from the Freight Module: 1 = Mid-size trucks, 2 = Rail

3) Calculate fuel consumption by mode:

$$TMFD_{IM,T} = TMOD_{IM,T} * TMEFFL_{IM,T} \quad \text{(B-232)}$$

where:

TMFD = Total mass-transit fuel consumption by mode

4) Regionalize consumption:

$$QMODR_{IM,IR,T} = TMFD_{IM,T} * \left[\frac{TMC_POPAFO_{IR,T}}{\sum_{IR=1}^{9} TMC_POPAFO_{IR,T}} \right] \quad \text{(B-233)}$$

where:

QMODR = Regional consumption of fuel, by mode
TMC_POPAFO = Regional population forecasts, from the Macro Module

RECREATIONAL BOATING DEMAND MODEL — Subroutine TMISC

Calculate recreational boat fuel use:

1) Calculate fuel demand:

$$RECFD_T = RECFD_{T-1} * \left[\frac{TMC_YD_T}{TMC_YD_{T-1}} \right]^{BETAREC} \quad \text{(B-234)}$$

where:

RECFD = National recreational boat gasoline consumption in year T
TMC_YD = Total disposable personal income, from the Macro Module
BETAREC = Coefficient of proportionality relating income to fuel demand for boats

2) Regionalize consumption according to population:

$$QRECR_{IR,T} = RECFD_T * \left[\frac{TMC_POPAFO_{IR,T}}{\sum_{IR=1}^{9} TMC_POPAFO_{IR,T}} \right] \quad \text{(B-235)}$$

where:

QRECR = Regional fuel consumption by recreational boats in year T

Calculate lubricant demand:

1) Sum freight truck VMT across size classes:

$$FTVMT_T = \sum_{SC=1}^{3} FVMTSC_{SC,T} \quad \text{(B-236)}$$

where:

FTVMT = Total freight truck VMT
FVMTSC = Freight truck VMT, by size class

2) Calculate total highway travel:

$$HYWAY_T = VMTEE_T + FTVMT_T + FLTVMT_T \quad \text{(B-237)}$$

where:

HYWAY = Total highway VMT
FLTVMT = Total fleet vehicle VMT, from the Fleet Module

3) Calculate lubricant demand:

$$LUBFD_T = LUBFD_{T-1} * \left[\frac{HYWAY_T}{HYWAY_{T-1}}\right]^{BETALUB} \quad \text{(B-238)}$$

where:

LUBFD = Total demand for lubricants in year T
BETALUB = Constant of proportionality, relating highway travel to lubricant demand

4) Regionalize lubricant demand:

$$QLUBR_{IR,T} = LUBFD_T * \left[\frac{\left(\left(VMTEE_T - FLTVMT_T\right) * SEDSHR_{V,IR,T}\right) + \left(FTVMT_T * SEDSHR_{F,IR,T}\right)}{HYWAY_T}\right] \quad \text{(B-239)}$$

where:

QLUBR = Regional demand for lubricants in year T, in Btu
SEDSHR = Regional share of fuel consumption, from SEDS
IF = Index of fuel type: gasoline for light-duty vehicles, diesel for freight trucks

VEHICLE EMISSIONS MODULE — Subroutine TEMISS

This subroutine calculates the emissions of six airborne pollutants, at every conceivable level of aggregation. A single, representative equation is provided.

1) Calculate disaggregate emissions of airborne pollutants:

$$EMISS_{IE,IM,IR,T} = EFACT_{IE,IM,IR,T} * U_{IM,IR,T} \quad \text{(B-240)}$$

where:

EMISS = Regional emissions of a given pollutant, by mode of travel

EFACT = Emissions factor relating measures of travel to pollutant emissions

U = Measure of travel demand, by mode: units in VMT for highway travel, gallons of fuel consumption for other modes

IM = Index of travel mode: references individual vehicle types used in the preceding modules, and may be further subdivided by size class, vehicle technology, and vehicle type

IE = Index of pollutants: 1 = SO_x, 2 = NO_x, 3 = C, 4 = CO_2, 5 = CO, 6 = VOC

IR = Index identifying census region

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Appendix D. Model Abstract

Model Name:

Transportation Sector Model

Model Acronym:

TRAN

Description:

The Transportation Sector Model incorporates an integrated modular design which is based upon economic, engineering, and demographic relationships that model transportation sector energy consumption at the nine Census Division level of detail. The Transportation Sector Model comprises the following components: Light Duty Vehicles, Light Duty Fleet Vehicles, Freight Transport (truck, rail, and marine), Aircraft, Miscellaneous Transport (military, mass transit, and recreational boats), and Transportation Emissions. The model provides sales estimates of 2 conventional and 14 alternative-fuel light duty vehicles, and consumption estimates of 12 main fuels.

Purpose of the Model:

As a component of the National Energy Modeling System integrated forecasting tool, the transportation model generates mid-term forecasts of transportation sector energy consumption. The transportation model facilitates policy analysis of energy markets, technological development, environmental issues, and regulatory development as they impact transportation sector energy consumption.

Most Recent Model Update:

December, 1993.

Part of Another Model?

National Energy Modeling system (NEMS).

Model Interfaces:

Receives inputs from the Electricity Market Module, Oil and Gas Market Module, Renewable Fuels Module, and the Macroeconomic Activity Module.

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Documentation:

Model Documentation Report: Transportation Sector Model of the National Energy Modeling System, March 1994.

Archive Media and Installation Manual(s):

The model will be archived on IBM 3380 tape compatible with the IBM 3090 mainframe system upon completion of the NEMS production runs to generate the Annual Energy Outlook 1994.

Energy System Described:

Domestic transportation sector energy consumption.

Coverage:

- Geographic: Nine Census Divisions: New England, Mid Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, Pacific.
- Time Unit/Frequency: Annual, 1990 through 2010.
- Products: Motor gasoline, aviation gasoline, diesel/distillate, residual oil, electricity, jet fuel, LPG, CNG, methanol, ethanol, hydrogen, lubricants.
- Economic Sectors: Forecasts are produced for personal travel, freight trucks, railroads, domestic and international marine, aviation, mass transit, and military use.

Model Interfaces:

Model outputs are provided to the Integrating Module, which then sends them back to the supply modules.

Model Structure:

Light-duty vehicles are classified according to the six EPA size classes for cars and light trucks. Freight trucks are divided into light-duty, medium-duty and heavy-duty size classes. The air transport module contains both wide- and narrow-body aircraft. Rail transportation is composed of freight rail and three modes of personal rail travel: commuter, intercity and transit. Shipping is divided into domestic and international categories.

Special Feautres:

The Transportation Sector Model has been created to allow the user to change various exogenous and endogenous input levels. The range of policy issues that the transportation model can evaluate are: fuel taxes and subsidies; fuel economy levels by size class; CAFE levels; vehicle pricing policies by size class; demand for vehicle performance within size classes; fleet vehicle sales by technology type; alternative-fuel vehicle sales shares; the Energy Policy Act; Low Emission Vehicle Program; VMT reduction; and greenhouse gas emissions levels.

Modeling Techniques:

The modeling techniques employed in the Transportation Sector Model vary by module: econometrics for passenger travel, aviation, and new vehicle market shares; exogenous engineering and judgement for MPG, aircraft efficiency, and various freight characteristics; and structural for light-duty vehicle and aircraft capital stock estimations.

Computing Environment:

- Hardware Used: IBM 3090
- Operating System: MVS
- Language/Software Used: VS FORTRAN, Ver 2.05
- Memory Requirement: 4098 K
- Storage Requirement: Model has not yet been archived. It will require an as-yet undetermined number of tracks of an IBM 3380 disk pack.
- Estimated Run Time: 2 minutes for a 1990-2015 run on non-iterating NEMS Mode on IBM 3090 mainframe
- Special Features: None.

Independent Expert Reviews Conducted:

Independent Expert Review of Transportation Sector Component Design Report, June, 1992, conducted by David L. Greene, Oak Ridge National Laboratory.

Status of Evaluation Efforts by Sponsor:

None.

DOE Input Sources:

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Non-DOE Input Sources:

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Appendix E. Data Quality and Estimation

LIST OF TABLES

Table E-1. Regression Results From The Market Share Model E-2
Table E-2. Alternative Fuel Vehicle Model Coefficients E-4
Table E-3. Model of VMT per Capita E-5
Table E-4. Fuel Consumption and Real (1982) Operating Costs E-6
Table E-5. Domestic Passenger Travel Demand—Preliminary Data E-7
Table E-6. International Passenger Travel Demand—Preliminary Data E-8
Table E-7. Passenger and Freight Travel Demand E-9
Table E-8. Total Yields (1982 Cents Per Passenger or Ton Mile) E-10

Appendix E. Data Quality and Estimation

This appendix presents results of the statistical tests conducted for those componenents of the transportation model which rely on econometric estimations. These components include: The Fuel Economy Model, the Alternative Fuel Vehicle Model, the Vehicle-Miles Traveled Model, and the Air Travel Demand Model. To date, no data quality studies have been conducted in order to validitate the transportation model's input data.

Fuel Economy Model

The methodology employed to assess the influence of macroeconomic and time-dependent variables on the mix of size classes and performance was log-linear regression analysis using historical data on car and light truck sales over the 1979-1990 period. Greater detail is provided in Attachment 1 of Appendix F.

The following equations were used to estimate the class market shares of new vehicle purchases:

<u>All Vehicle Classes Except Luxury Cars:</u>[1]

$$\ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{YEAR} - \ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{1990} = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR} - \$13{,}000}{INCOME_{1990} - \$13{,}000}\right) \quad \text{(E-1)}$$

where:

$CLASS\$SHARE_i$ = The market share of the ith vehicle class
FUELCOST = The price of gasoline
INCOME = Per capita disposable income

[1]Note: Market shares for Mini and Sub-Compact cars are solved jointly. The resulting combined market share is allocated between the two classes based on the original 1990 allocation. Special treatment of these two classes was made necessary by the small sample size in the analysis data sets.

Luxury Cars:

$$\ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{YEAR} - \ln\left(\frac{CLASS\$SHARE_i}{1 - CLASS\$SHARE_i}\right)_{1990} = A * \ln\left(\frac{YEAR}{1990}\right) + B * \ln\left(\frac{FUELCOST_{YEAR}}{FUELCOST_{1990}}\right) + C * \ln\left(\frac{INCOME_{YEAR}}{INCOME_{1990}}\right) \quad (E\text{-}2)$$

The values of the coefficients with their associated T-statistics are provided below in Table E-1.

Table E-1. Regression Results From The Market Share Model

Group	F Val	R^2	Intercept	YEAR	FUELCOST	INCOME
Mini and Subcompact	14.359	0.891	-5.428	0.056 (1.761)	1.33 (1.828)	-0.169 (-1.524)
Sports	11.193	0.808	-2.475	-0.049 (-1.903)	0.26 (.466)	.0068 (.059)
Compact	5.533	0.76	-5.021	0.111 (2.117)	1.332 (1.35)	0.107 (.52)
Intermediate	3.[illegible]	[illegible].536	-1.01	-0.051 (-1.742)	-0.213 (-.335)	-0.0017 (-.013)
Large	16.880	0.864	-3.312	-0.119 (-4.754)	0.042 (.077)	0.231 (2.018)
Luxury	18.458	0.939	-3.1	0.126 (2.336)	1.166 (2.704)	0.169 (1.441)
Mini Truck	1.378	0.341	2.268	-0.018 (-.168)	-3.648 (-1.6)	-0.968 (-2.027)
Compact Pickup	19.183	0.916	-8.749	-0.042 (-1.238)	-0.811 (-1.48)	0.174 (1.247)
Compact Van	804.167	0.998	-9.3	0.01 (.352)	0.832 (1.727)	0.307 (3.045)
Compact Utility	274.104	0.994	-7.36	-0.042 (-1.447)	-0.2 (-.396)	0.366 (2.933)
Standard Size Trucks	1.582	0.475	-2.779	-0.056 (-1.523)	0.252 (.307)	0.144 (.846)

Alternative Fuel Vehicle Model

The AFV model uses a multinomial nested logit approach to estimate market shares of sixteen vehicle technologies. Model coefficients are taken from a study sponsored by the California Energy Commission, using a stated preference survey of California residents. The applicability of this study to a nationwide model has not been tested. Market shares are based on the exponentiated value of the consumer utility function, represented as follows:

$$\begin{aligned} VC1_{IT,IR} = {} & CONST_{IT} + \beta_1 VPRI_{IS,IT,N} + \beta_2 COPCOST_{IT,IS,IR,N} \\ & + \beta_3 VRANGE_{IS,IT,N} + \beta_4 VRANGE^2_{IS,IT,N} + \beta_5 EMISS_{IS,IT,N} \\ & + \beta_6 EMISS^2_{IS,IT,N} + \beta_7 FAVAIL_{IT,IR,N} + \beta_8 FAVAIL^2_{IT,IR,N} \end{aligned} \quad \text{(E-3)}$$

where:

VC1 = Utility vector for conventional and alternative vehicles
CONST = Constant associated with each considered technology *IT*
VPRI = Price of each considered technology in 1990$
VRANGE = Vehicle range of the considered technology
EMISS = Emissions levels relative to gasoline ICE's
FAVAIL = Relative availability of the considered fuel

Model coefficients and relevant T-statistics are provided in Table E-2, on the following page. An extensive description of the data base development process is provided as an attachment in Appendix F.

Table E-2. Alternative Fuel Vehicle Model Coefficients

VARIABLE	COEFFICIENT	T-STATISTIC
VPRI	-.134	10.1
COPCOST	-.190	16.4
VRANGE	2.52	11.4
$VRANGE^2$	-.408	7.4
EMISS	-2.45	7.0
$EMISS^2$	0.855	2.7
FAVAIL	2.96	5.7
$FAVAIL^2$	-1.63	3.5
CONST (Technology-Specific, as Follows)		
Gasoline	0.0	—
Diesel	0.0	—
Ethanol Flex	0.693	6.7
Ethanol Neat	0.0979	0.9
Methanol Flex	0.693	6.7
Methanol Neat	0.0979	0.9
Electric	-.0240	0.1
Electric Hybrid/Large ICE	-.257	1.5
Electric Hybrid/Small ICE	-.257	1.5
Electric Hybrid/Turbine	-.257	1.5
CNG	0.0979	0.9
LPG	0.0979	0.9
Turbine/Gasoline	0.0	—
Turbine/CNG	0.0979	0.9
Fuel Cell/Methanol	0.0979	0.9
Fuel Cell/Hydrogen	0.0979	0.9

Vehicle-Miles Traveled Model

Vehicle-miles traveled is estimated on a per capita basis using a generalized difference equation, estimated using the Cochrane-Orcutt iterative procedure:

$$VMTPC_T = \rho VMTPC_{T-1} + 0.28(1-\rho) - 7.50(CPM_T - \rho CPM_{T-1}) + 3.6 \times 10^{-4}(YPC_T - \rho YPC_{T-1}) + 8.36(PrFem_T - \rho PrFem_{T-1}) \quad \text{(E-4)}$$

where:

CPM = The cost of driving a mile
YPC = Disposable personal income per capita
PrFem = The ratio of per capita female driving to per capita male driving.

The parameters and relevant T-statistics are provided in Table E-3, below.

Table E-3. Model of VMT per Capita

	ρ	Constant	CPM	YPC	PrFem	Adj. R-Sq
Parameter T-Statistic	0.72	0.28	-7.50 -2.32	3.6e-04 2.46	8.36 2.99	0.841

Air Travel Demand Model

The following tables (E-4 - E-8) provide the data used in the air travel demand regressions. All data manipulation is described in the accompanying notes.

Table E-4. Fuel Consumption and Real (1982) Operating Costs

YEAR	DOMESTIC			INTERNATIONAL		
	Fuel Cons. (10^6 Gal.) (JFD_D)	Cost/Gal (PJF_D)	Non-Fuel Costs/ASM ($OPCST_D$)	Fuel Cons. (10^6 Gal.) (JFD_{INT})	Cost/Gal (PJF_I)	Non-Fuel Costs/ASM ($OPCST_I$)
1979	8,866	72	6.23	1,828	82	6.28
1980	8,519	101	6.34	1,747	119	5.94
1981	8,555	109	6.17	2,033	122	5.07
1982	8,432	97	5.85	1,968	108	4.72
1983	8,673	85	5.87	1,998	93	4.90
1984	9,626	78	5.51	2,286	83	4.97
1985	10,115	72	5.65	2,488	76	4.79
1986	11,137	48	5.89	2,545	54	5.17
1987	11,587	47	6.00	2,894	51	5.25
1988	11,918	43	6.28	3,263	47	5.72
1989	11,905	47	6.69	3,557	50	6.02
1990	12,429	58	6.60	3,963	64	6.48

Sources:

JFD & PJF: U.S. Department of Transportation, Research and Special Programs Administration (RSPA), *Fuel Cost And Consumption Tables*, annual summaries, 1979-1990.

OPCST: Non-Fuel operating costs derived from U.S. Department of Transportation, Research and Special Programs Administration, *Air Carrier Financial Statistics Quarterly, December 1990/1989*, and prior issues, "Total Operating Expenses", Line 28, minus Fuel Costs from RSPA fuel consumption tables, *op. cit.* The result is subsequently divided by Available Seat Miles, from U.S. Department of Transportation, Research and Special Programs Administration, *Air Carrier Traffic Statistics Monthly, December 1990/1989*, and prior issues, Lines 12, 42.

Table E-5. Domestic Passenger Travel Demand—Preliminary Data

YEAR	Total Travel (RPM_D)	Business Fraction (BFRAC)	Available Seat-Miles (ASM_D)
1979	212,701	0.55	337,668
1980	204,367	0.54	350,716
1981	201,435	0.52	349,824
1982	213,631	0.52	364,301
1983	232,165	0.51	386,138
1984	250,686	0.48	432,781
1985	277,836	0.50	455,099
1986	307,884	0.46	505,734
1987	329,214	0.48	533,169
1988	334,290	0.50	544,737
1989	335,213	0.49	537,133
1990	345,763	0.48	570,387

Sources:

(1) **RPM:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Traffic Statistics Monthly, December 1990/1989,* and prior issues. Lines 9, 41.
Passenger Revenue: U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Financial Statistics Quarterly, December 1990/1989,* and prior issues. Lines 1, 2, 12.

(2) **RTM:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Traffic Statistics Monthly, December 1990/1989,* and prior issues. Lines 18-21, 46.
Freight Revenue: U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Financial Statistics Quarterly, December 1990/1989,* and prior issues. Lines 6, 7, 13.

Table E-6. International Passenger Travel Demand—Preliminary Data

YEAR	Total, U.S. Carrier ($RPM_{t,US}$)	Available Seat-Miles ($ASM_{t,US}$)	Departures, U.S. Carrier (DEP_{US})	Departures, Foreign Carrier (DEP_{FOR})	Miles per Int. Departure (MPID)
1979	57,017	87,743	9,124	8,958	3,125
1980	63,355	97,762	9,369	9,886	3,381
1981	58,629	89,013	9,581	10,330	3,060
1982	58,803	91,637	9,485	9,837	3,100
1983	61,823	93,510	9,888	9,837	3,126
1984	68,818	101,324	10,531	11,076	3,267
1985	73,237	110,578	10,696	11,791	3,424
1986	71,038	117,339	10,711	12,464	3,316
1987	88,615	137,701	12,853	13,811	3,447
1988	103,358	151,601	14,981	14,440	3,450
1989	112,266	166,755	15,687	15,466	3,578
1990	126,392	182,724	17,628	16,418	3,585

Sources:

Fraction of Business Travel: Air Transport Association of America, *Air TravelSurvey, 1990,* Washington D.C.
International Passenger Departures: U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA, *U.S. International Air Travel Statistics,* annual issues, Table Id/IId.

Table E-7. Passenger and Freight Travel Demand

YEAR	DOMESTIC			INTERNATIONAL		FREIGHT
	Business ($RPM_{D,B}$)	Personal ($RPM_{D,P}$)	Load Fac (LF_D)	Total (RPM_I)	Load Fac (LF_I)	D & I (RTM)
1979	116,986	95,715	0.63	56,498	0.65	8,350
1980	109,336	95,031	0.58	65,103	0.65	9,136
1981	104,746	96,689	0.58	60,921	0.66	9,033
1982	110,020	103,611	0.59	59,894	0.64	9,086
1983	118,404	113,761	0.60	61,664	0.66	9,713
1984	120,329	130,357	0.58	70,599	0.68	10,766
1985	138,918	138,918	0.61	76,986	0.66	10,515
1986	141,627	166,257	0.61	76,851	0.61	12,228
1987	158,023	171,191	0.62	91,917	0.64	14,466
1988	167,145	167,145	0.61	101,492	0.68	16,066
1989	164,254	170,959	0.62	111,475	0.67	17,824
1990	165,966	179,797	0.61	122,054	0.69	17,922

International RPM associated with passengers departing the United States is inferred from available data, as follows:

1) The Department of Transportation estimates total (departures and arrivals) international RPM for only U.S. carriers. This estimate is divided by two to estimate the RPM associated with international departures.
2) This figure (RPM for U.S. carrier departures) is divided by the number of passengers departing on U.S. carriers to obtain miles per departure.
3) Assuming that this quotient (miles per departure) also characterizes foreign carriers' trips, and further assuming equal load factors, passenger departures of both U.S. and foreign carriers are added, then multiplied by the above factor to get an estimate of total international RPM.
4) Yields will be estimated using only data for U.S. carriers' international operations and will be attributed to foreign carriers, as well.

Table E-8. Total Yields (1982 Cents Per Passenger or Ton Mile)

YEAR	PASSENGER[1]			FREIGHT[2]
	Domestic		International	
	Business ($YIELD_B$)	Personal ($YIELD_P$)	($YIELD_I$)	($YIELD_F$)
1979	11.32	11.32	9.53	43.23
1980	13.29	13.29	9.18	41.76
1981	13.47	13.47	8.72	39.64
1982	11.91	11.91	8.43	35.90
1983	11.41	11.41	8.73	33.14
1984	11.64	11.64	8.20	31.84
1985	10.82	10.82	7.94	31.82
1986	9.66	9.66	8.11	47.97
1987	9.70	9.70	8.05	45.45
1988	10.11	10.11	8.26	46.38
1989	10.31	10.31	7.89	39.52
1990	10.18	10.18	8.09	33.86

Sources:

(1) **RPM:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Traffic Statistics Monthly, December 1990/1989,* and prior issues. Lines 9, 41. **Passenger Revenue:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Financial Statistics Quarterly, December 1990/1989,* and prior issues. Lines 1, 2, 12.

(2) **RTM:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Traffic Statistics Monthly, December 1990/1989,* and prior issues. Lines 18-21, 46. **Freight Revenue:** U.S. Department of Transportation, Research and Special Projects Administration (RSPA), *Air Carrier Financial Statistics Quarterly, December 1990/1989,* and prior issues. Lines 6, 7, 13.

Parameter Estimation Details

The equations used to forecast air travel demand are presented below, along with relevant statistical information.

1. Calculate the cost per mile of air travel (the following equation corresponds to Equation 103 in Volume I):

$$\begin{array}{lcc} \text{YIELD} = 4.22 + & .94\,\text{PJF} + & 65.42\,\text{OPCST} \\ \text{Std. Err.} & (.016) & (7.59) \\ \text{T-Statistic} & 58.95 & 8.62 \end{array} \qquad \text{(E-5)}$$

$$\text{Adj. } R^2 = .997 \;;\quad \text{D-W} = 1.06$$

where:

YIELD = Cost of air travel, expressed in cents per RPM
PJF = Price of jet fuel, in dollars per million Btu
OPCST = Non-fuel operating costs, in dollars per available seat-mile

2. Calculate annual the revenue passenger miles for business travel (the following equation corresponds to Equation 104 in Volume I):

$$\begin{array}{lcc} \text{RPMBPC} = -587.8 + .118\,\dfrac{\text{TMC_GDP}}{\text{TMC_POPAFO}} & - & 20.56\,\text{YIELD} \\ \text{Std. Err.} & (.010) & (5.90) \\ \text{T-Statistic} & 5.0 & -2.17 \end{array} \qquad \text{(E-6)}$$

$$\text{Adj. } R^2 = .947 \;;\quad \text{D-W} = 2.42$$

where:

RPMBPC = Revenue passenger miles for business travel
TMC_GDP = Gross domestic product, in 1987 dollars.
TMC_POPAFO = U.S. population

3. Calculate the revenue passenger miles for personal travel (the following equation corresponds to Equation 105 in Volume I):

$$RPMPPC = -126.8 + .050 \frac{TMC_YD}{TMC_POPAFO} - 12.80\, YIELD \qquad \text{(E-7)}$$

Std. Err.	(.027)	(10.51)
T-Statistic	4.32	-1.96

Adj. R^2 = .940 ; D-W = 1.44

where:

TMC_GDP = Gross domestic product, in 1987 dollars.
TMC_YD = Per capita disposable personal income, in 1987 dollars.
TMC_POPAFO = U.S. population
PCTINT = Proportionality factor relating international to domestic travel levels

4. Calculate the revenue ton-miles of air freight (the following equation corresponds to Equation 107 in Volume I):

$$RTM = (-18{,}165.6 + 22.35\, EXDN87 + 5.77\, GDP) \cdot DFRT \qquad \text{(E-8)}$$

Std. Err.	(6.04)	(.740)
T-Statistic	3.70	7.79

Adj. R^2 = .940 ; D-W = 1.44

where:

RTM = Revenue ton-miles of freight
TMC_EXDN87 = Value of merchandise exports, in 1987 dollars
TMC_GDP = Gross domestic product, in 1987 dollars.
DFRT = Fraction of freight ton-miles transported by dedicated carriers

MODEL DOCUMENTATION REPORT: TRANSPORTATION SECTOR MODEL OF THE NATIONAL ENERGY MODELING SYSTEM

Appendix F - Attachments

March 1994

Office of Integrated Analysis and Forecasting
Energy Information Administration
US Department of Energy
Washington, DC

This report was prepared by the Energy Information Administration, the independent statistical agency within the Department of Energy. The information contained herein should not be construed as advocating or reflecting any policy position of the Department of Energy or any other organization.

Appendix F. Attachments to the Transportation Model

TABLE OF CONTENTS

Attachment 1: Fuel Economy Model F-2
- INTRODUCTION F-2
- METHODOLOGY F-3
- RESULTS F-4

Attachment 2: Alternative Fuel Vehicle Model F-10
- INTRODUCTION F-10
- DESCRIPTION OF VEHICLE TECHNOLOGIES F-14
- VEHICLE PRICES F-21
- VEHICLE EFFICIENCY F-34
- VEHICLE EMISSIONS F-40
- FUEL OPERATING COST F-48
- FUEL AVAILABILITY F-55
- VEHICLE RANGE F-59

Attachment 3: LDV Stock Module F-66
- INTRODUCTION F-66
- BACKGROUND F-66
- FUEL EFFICIENCY GAP PROJECTIONS F-75

Attachment 4: Vehicle-Miles Traveled Model F-94
- INTRODUCTION F-94
- METHODOLOGY F-95

Attachment 5: Air Travel Module F-100

Attachment 6: Vehicle Emissions Module F-104
- INTRODUCTION F-104
- HIGHWAY MOBILE SOURCE EMISSION FACTORS F-105
- OFF-HIGHWAY SOURCES EMISSIONS FACTORS F-130

LIST OF TABLES

Table F-1. Regression Results From LDV Market Share Model F-5
Table F-2. Regression Results From LDV Performance Model F-7
Table F-3: LDV Performance Model Elasticities F-7
Table F-4. LDV Performance and Price Options F-8
Table F-5. Gasoline Vehicle Characteristics (1990) F-23
Table F-6. AFV Price Premia by Technology F-31
Table F-7. LDV and AFV Cost Decay Rates F-32
Table F-8. Current Mid-Sized Vehicle Fuel Efficiencies F-36
Table F-9. Annual LDV & AFV Efficiency Gain, by Technology (Three Scenarios) F-38
Table F-10. Base Mid-Sized Vehicle Emissions (Grams/Mile, 1990) F-42
Table F-11. Minimum Possible Emissions, Mid-Size Vehicle (Grams/Mile, 2030) F-43
Table F-12. Pollutant Impact Weighting Factors (Health vs. Environment) F-45
Table F-13. LDV & AFV Emissions Decay Rates F-45
Table F-14. Average Fuel Prices, $1990 . . . . . F-49
Table F-15. Regional Fuel Price Differences F-50
Table F-16. Fuel Price Escalation Rates F-52
Table F-17. Base Year (1990) Fuel Availability, by Region F-56
Table F-18. Availability Gap Closure Rates, By Scenario F-58
Table F-19. Current Small Vehicle Range and Size Range Credit F-61
Table F-20. Automobile Fuel Efficiency Gap Projections: Logistic Growth of City Driving Share F-79
Table F-21. Light Truck Fuel Efficiency Gap Projections: Logistic Growth of City Driving Share F-79
Table F-23. Light Truck Fuel Efficiency Gap Projection: Logistic Growth of Average Highway Speed . F-84
Table F-24. Congestion Index Value for Selected Cities F-87
Table F-25. 1987 Urban Area Rankings by Congestion Index and Cost per Capita F-88
Table F-26. Urban Freeway Congestion Statistics F-90
Table F-27. Automobile Fuel Efficiency Gap Projections: Logistic Increasing Congestion Trend F-90
Table F-28. Light Truck Fuel Efficiency Gap Projections: Logistic Increasing Congestion Trend F-93
Table F-29. Total Fuel Efficiency Gap Projections for Automobiles and Light Duty Trucks F-93
Table F-30. VMT Variable Correlation Coefficients F-95
Table F-31. VMT Linear Regression Output F-96
Table F-32. VMT Generalized Difference Equation Output F-96
Table F-33. Average Annual VMT Growth Rates F-98

LIST OF TABLES (Cont.)

Table F-34. ATA 1990 Air Travel Survey Data F-103
Table F-35. Adjusted MOBILE4.1 Emission Factors F-122
Table F-36. EPA Highway Vehicle Classification Categories and Definitions F-124
Table F-37. LDV Sulfur Dioxide and Carbon Dioxide Emission Factors (Grams/Mile) F-127
Table F-38. Lifetime Average Emission Factors for Alternative Fuel Vehicles (Grams per Mile) F-129
Table F-39. TRAN Locomotive Emission Factors F-132
Table F-40. TERF Aircraft Emission Factors F-137
Table F-41. Aircraft Emissions Data F-138
Table F-42. Commercial Vessel Emission Factors F-146
Table F-43. Recreational Marine Vessel Emission Factors F-147
Table F-44. Ocean-Going Commercial Vessel Emission Factors F-148
Table F-45. Harbor and Fishing Vessel Emission Factors F-149

LIST OF FIGURES

Figure F-1. Urban Share of Automobile VMT: Logistic Forecast F-73
Figure F-2. Urban Share of Automobile VMT: Logistic and Linear Forecasts F-74
Figure F-3. Urban Share of Automobile VMT: 1953-1990 . . . . . F-76
Figure F-4. Urban Share of Light Truck VMT: 1966-1990 . . . . . F-77
Figure F-5. Average Vehicle Highway Speed: 1945-1990 . . . . . F-82
Figure F-6. Percent of Highway VMT over 55 MPH: 1981-1990 . . . . . F-83
Figure F-7. Fuel Efficiency Gap for Automobiles (with Adjusted Driving Share) F-91
Figure F-8. Fuel Efficiency Gap for Light Duty Trucks (Logistic Forecast) F-92
Figure F-9. VMT Demographic Adjustment Factor: 1970-2030 . . . . . F-97
Figure F-10. VMT Per Capita: 1970-2030 . . . . . F-98
Figure F-11. Linear VMT Projections F-99
Figure F-12. VMT Point Elasticities: 1970-2030 . . . . . F-99
Figure F-13. Demographic Adjustment Index for Personal Air Travel: 1980-2040 . . . F-103

Appendix F. Attachments to the Transportation Model

The attachments contained within this appendix provide additional details about the model development and estimation process which do not easily lend themselves to incorporation in the main body of the model documentation report. The information provided in these attachments is not integral to the understanding of the model's operation, but provides the reader with to opportunity to gain a deeper understanding of some of the model's underlying assumptions. There will be a slight degree of replication of materials found elsewhere in the documentation, made unavoidable by the dictates of internal consistency. Each attachment is associated with a specific component of the transportation model; the presentation follows the same sequence of modules employed in Volume I.

The following attachments are contained in Appendix F:

Attachment 1: Fuel Economy Model (FEM): Provides a discussion of the FEM vehicle demand and performance by size class models.

Attachment 2: Alternative Fuel Vehicle (AFV) Model: Describes data input sources and extrapolation methodologies.

Attachment 3: Light-Duty Vehicle (LDV) Stock Model: Discusses the fuel economy gap estimation methodology.

Attachment 4: Vehicle-Miles Traveled (VMT) Model: Presents the development of the updated VMT forecasting methodology.

Attachment 5: Air Travel Demand Model: Presents the derivation of the demographic index, used to modify estimates of personal travel demand.

Attachment 6: Airborne Emissions Model: Describes the derivation of emissions factors used to associate transportation measures to levels of airborne emissions of several pollutants.

Attachment 1: Fuel Economy Model

Demand Models for Vehicle Size Class Mix
and Performance by Size Class

INTRODUCTION

Estimates of the future mix of vehicle classes sold and the performance level by size class requires a detailed econometric demand model of vehicle choice by size class and vehicle performance within size class. There are a few publicly available models that forecast vehicle demand by size class, but those models have proved inaccurate in the past, and do not use a class structure that is compatible with the one used in the FEM. Demand for performance has not been assessed to date in any publicly available study. Both the size mix and performance levels are difficult to estimate because the car purchase decision is complex and consumer choice depends not only on the macroeconomic conditions but also on the attributes of individual products in the marketplace. Some of these attributes are based on the styling of the car, its perceived quality, the manufacturer's image and the status conveyed by owning a specific model, and cannot be easily quantified. Although these variables affect choice of individual models, they can also affect the choice of vehicle sizes or performance levels. For example, many consumers appeared to willing to buy a Japanese car for its quality and reliability even if it's size was smaller than the size actually desired by consumers. There have also been changes in consumer performance that may be linked to demographic variables, e.g., older consumers prefer larger cars.

These factors have made the automotive market notoriously difficult to forecast. The models incorporated in the FEM do <u>not</u> represent an attempt to provide a comprehensive forecast of future shifts in size class mix or performance levels by size class in response to the potentially large range of influencing or causal variables. Rather, the models attempt to capture the response to broad macroeconomic forces or behavioral (time) trends based on the experience of the last 15 years. It is recognized that these models are relatively simplistic, and it is anticipated that future versions of the FEM will incorporate more advanced models.

METHODOLOGY

The methodology employed to assess the influence of macroeconomic and time dependent variables on the mix of size classes and performance was by regression analysis of historical data.

EEA has compiled a very large data base on car and light truck sales over the 1979-1990 period. These data are based on the official CAFE files from EPA, augmented by the addition of vehicle and engine descriptor variables. All of the vehicles were classified by market class according to the scheme utilized in the FEM. Vehicle performance levels were measured by the horsepower to weight ratio (HP/WT) that is well correlated to objective measures such as the 0 to 60 mph acceleration time. Detailed weight data was unavailable for light trucks, and horsepower alone was used as a surrogate for performance. (Fortunately, truck weight within market class did not change significantly in the 12 year period analyzed).

The models for size class mix and performance utilized the same set of independent variables

- Disposable income per capita (in 1990 dollars)
- Price of gasoline (1990 dollars)
- Vehicle price average by class
- Vehicle fuel economy
- Rate of change of gas price over two years
- Cost of driving per mile
- Number of nameplates (models) in a class

The last variable is really a composite of fuel cost/fuel economy and not a new independent variable.

Performance was defined as the average HP/WT ratio by class for cars, and the average HP by class for trucks. Market share was defined as the sales fraction of the class relative to <u>entire car and light truck</u> market. This definition was chosen to incorporate the effects of consumers switching from cars to light trucks.

In general, the models were linear regressions of the logarithm of all variables, so that the co-efficients represented "elasticity" estimates. However, the market share model was modified to utilize the variable (m/1-m) as the independent variable in the regression, for two reasons. First,

the elasticity of market share appears to be dependent on how large a share of the market a size class has. This reflects the fact that at very low market shares, buyers of a particular class are reduced to the diehard consumers who are less likely to switch due to macroeconomic forces, and the market is inelastic. Second the log(m/1-m) form converts a 0 to 1 variable to one that spans the -infinity to +infinity range. As a result of this variable change the model cannot be driven to m=1 for any input set, so that no one market class takes over the entire market for any combination of inputs. Such a variable form has been utilized in prior analysis by Wheaton Econometric Forecasting Associates (WEFA).

RESULTS

A stepwise linear regression of performance by market class and of class market share was performed to aid in the selection of independent variables with the greatest statistical significance. In addition, the co-efficients were required to be

- directionally consistent with intuitive expectations
- consistent in absolute magnitude across market classes that are similar

For the market share regressions, the variables that were statistically significant included: model year (time), price of gasoline, disposable income, number of nameplates (in some classes). In particular, number of nameplates was significant in those classes where only one or two makes existed in the early 1980's but new makes were introduced in the mid-to-late 1980's; compact vans are a good example of this phenomenon.

Table F-1 shows the results of the regressions of (m_i/1-m_i) against the variables MDLY (model year), LPGAS (price of gasoline), LYD (per capita disposable income), and LNPLT (number of nameplates). The following conclusions are appropriate:

- Subcompact and minicompact market share benefits from a time trend towards smaller cars. Market share increases with increasing gasoline prices (1.33 co-efficient) but decreases with increasing income.
- Sports cars market share appears to be declining with time but is insensitive to price of gasoline or income.
- Compact car market share increase with time and increasing price of gasoline, but is insensitive to income trends.

Table F-1. Regression Results From LDV Market Share Model

Group	F Val	R^2	Intercept	MDLY	LPGAS	LYD	LNPLT
Mini and Subcompact	14.359	0.891	-5.428	0.056 (1.761)	1.33 (1.828)	-0.169 (-1.524)	1.136 (2.288)
Sports	11.193	0.808	-2.475	-0.049 (-1.903)	0.26 (.466)	.0068 (.059)	
Compact	5.533	0.76	-5.021	0.111 (2.117)	1.332 (1.35)	0.107 (.52)	0.383 (.825)
Intermediate	3.084	0.536	-1.01	-0.051 (-1.742)	-0.213 (-.335)	-0.0017 (-.013)	
Large	16.880	0.864	-3.312	-0.119 (-4.754)	0.042 (.077)	0.231 (2.018)	
Luxury	18.458	0.939	-3.1	0.126 (2.336)	1.166 (2.704)	0.169 (1.441)	-0.435 (-.699)
Mini Truck	1.378	0.341	2.268	-0.018 (-.168)	-3.648 (-1.6)	-0.968 (-2.027)	
Compact Pickup	19.183	0.916	-8.749	-0.042 (-1.238)	-0.811 (-1.48)	0.174 (1.247)	1.91 (5.122)
Compact Van	804.167	0.998	-9.3	0.01 (.352)	0.832 (1.727)	0.307 (3.045)	1.466 (16.421)
Compact Utility	274.104	0.994	-7.36	-0.042 (-1.447)	-0.2 (-.396)	0.366 (2.933)	0.763 (8.474)
Standard Size Trucks	1.582	0.475	-2.779	-0.056 (-1.523)	0.252 (.307)	0.144 (.846)	

- Intermediate car market share is decreasing with time but is largely insensitive to either the price of gasoline or income.
- Large car market share decreases with time, but increases with income.
- Luxury car market share increases with time, income and the price of gasoline.
- Minitruck market share is very sensitive to the price of gasoline, and decreases with increasing gasoline prices and income.
- Compact trucks and utilities market share are negatively influenced by time trends and price of gas, but positively by income.
- Compact vans have a unique trend relative to all trucks in showing increasing market share with increasing gasoline prices. It is also positively influenced by increasing income.
- Full size trucks (pickup, van and utility) show relatively stable market shares, with

a modestly declining time trend. Only utility vehicles' market share appear to be sensitive to income, while market shares of all full size trucks are insensitive to the price of gasoline.

Some of these trends initially appear to be counterintuitive, but one must consider the impact of a particular variable on sales of the class as well as the total fleet sales. For example, while sales of luxury cars decreases with increasing gasoline prices, the market share increases since sales of all other cars decline by a greater amount for the same change in the price of gasoline. Sales of minitrucks and compact pickup and utility vehicles, most of which are used for personal transportation or recreation, are also more strongly affected by increasing price of gasoline, and their market share drops. On the other hand, standard size vehicles are used more commonly in the light commercial sector or for hauling rather than personal transportation and their market shares are relatively stable in response to gasoline prices.

It should be noted that the co-efficients in Table F-1 are not elasticities as the dependent variable is $m_i/1-m_i$, not m_i alone. In general, the values of m_i range from 0.05 to 0.20. The correct "elasticity" co-efficient is the actual co-efficient times $1-m_i/2$, so that multiplying the co-efficients in Table F-1 by 0.4 ~ 0.475 will provide an estimate of elasticity.

The performance model utilized a similar procedure, but the dependent variable was average HP/WT (or HP for trucks) by class. The most significant variables were found to be LFC (fuel consumption), personal income (LYD) and price of gas (LPGAS) in most cases. In some cases, cost per mile (LCPM) provided a better regression when substituted for LFC and LPGAS. The results of the regression are shown in Table F-2. In general, the regressions yield the elasticities presented in Table F-3.

The results indicate that virtually all classes respond similarly to the cost of driving, although for small cars (mini-, sub-, and compact cars) an equivalent result was obtained for fuel economy rather than cost per mile. Performance demand is more sensitive to disposable income, with the large trucks showing very high sensitivity. This particular finding is suspect and may be due to the fact that significant engine improvements in the late 1980's (which increased rated HP) occurred in the same time frame when incomes were rising.

Table F-2. Regression Results From LDV Performance Model

Group	F Val	R^2	Intercept	LFC	LYD	LPGAS
Mini and Subcompact	14.819	0.848	13.893	-0.238 (1.706)	1.012 (-2.270)	0.11 (-.811)
Sports	7.675	0.742	-1.104	-0.311 (1.299)	-0.533 (.666)	-0.364 (1.616)
Compact	11.613	0.813	20.709	-0.252 (3.094)	1.721 (-3.308)	0.403 (-2.679)
Intermediate	57.101	0.956	14.252	-0.099 (.845)	1.114 (-3.296)	-0.0051 (.050)
Large	72.509	0.964	10.429	-0.168 (1.380)	0.704 (-1.902)	-0.171 (1.535)
Luxury	151.145	0.983	11.085	-0.124 (1.859)	0.79 (-2.704)	-0.248 (2.912)
Mini Truck	0.219	0.076	0.88	0.378 (.550)	0.483 (.230)	0.035 (.056)
Compact Pickup	35.043	0.929	-9.264	-0.119 (-.646)	1.409 (3.045)	0.03 (.228)
Compact Van	57.789	0.956	-33.712	-0.853 (-2.375)	3.722 (2.960)	-0.0044 (-.012)
Compact Utility	21.804	0.891	-10.507	0.586 (2.824)	1.785 (2.149)	-0.063 (-.264)
Standard Pickup	16.854	0.863	-17.358	0.276 (1.315)	2.41 (3.182)	0.271 (1.257)
Standard Van	37.117	0.933	-14.171	0.142 (1.061)	2.038 (4.393)	0.195 (1.72)
Standard Utility	21.177	0.888	-19.425	0.331 (2.144)	2.54 (3.398)	0.253 (1.176)

Table F-3: LDV Performance Model Elasticities

	LFC	LYD	LPGAS	LCPM
Small Cars	-0.23 ~ -0.30	+1 to +1.7	N.S.	--
Large Cars	-0.10 ~ -0.17	0.7 to 1.0	Variable	-0.1 to -0.20
Small Trucks	N.S.	+1.4 to +1.7	N.S.	-0.24 to -0.33
Standard Trucks	N.S.	-2.0 to 2.5	N.S.	-0.23 to -0.35

N.S. - Not Specified

VALUE OF PERFORMANCE AND FUEL ECONOMY ADJUSTMENT

The value of performance is defined as the dollar amount that consumers are willing to pay for horsepower. This value was estimated from the actual list price for the vehicles in the 1988-1990 period and was based on the engine option prices. This method assumes that the manufacturers are pricing horsepower at levels that consumers are willing to pay. Most domestic models offer an optional engine with higher HP, while several import models offer optional turbocharged engines or 4-valve engine versions. In each case the cost of the engine option alone was identified from manufacturer price lists for 1989/1990 models (very often, the engine option is available with other features such as performance tires, aerodynamic devices etc. so that the vehicle price is higher than the cost of the engine option). Based on the prices of engine options, the following averages are applicable for all cars except sports and luxury cars:

Table F-4. LDV Performance and Price Options

Engine Option	HP Gain (%)	Price	Price/% HP
4-Valve vs. 2-Valve	30 to 35	$400 to 500	13.30 to 16.66
V-6 vs. I-4	25 to 30	$300 to 400	12 to 16
V-8 vs. V-6	30 to 35	$400 to 500	13.30 to 16.66
Turbo vs. Nat Aspirated	45 to 60	$650 to 850	14.44 to 18.88

Based on these data, an approximate average value of performance is $15 per percent increase in HP. Most sports and several luxury cars charge prices that are 15 to 25 percent higher than the values quoted above (although some very high priced luxury cars such as Mercedes, Porsche, and BMW charge more than twice the values quoted above). Accordingly, the value of performance for these classes has been set to $18 per percent increase in HP.

Increasing performance also decreases fuel economy and this relationship is derived from a regression analysis of fuel economy data that provides the sensitivity of fuel economy to factors that increase performance. In general, performance can be increased by four methods:

- by increasing the axle ratio
- by installing a larger engine with the same number of cylinders
- by installing a larger engine with more cylinders
- by utilizing 4-valve heads or turbocharging

The first method is suitable only for small changes in performance (less than 10 percent). The second method is useful for changes in the range of 10 to 25 percent. The use of engines with more cylinders can result in HP gains of 30 to 60 percent (4 cylinder to 6 cylinder, or 6 cylinder to 8 cylinder). 4-valve engines generally provide HP gains of 20 to 25 percent relative to a 2-valve engine of equal displacement, while turbocharging can provide an HP increase of 40 to 45 percent relative to a naturally aspirated engine of equal displacement. These technologies can be combined with displacement increases or decreases to achieve any desired result.

Based on engineering and regression analysis (see Appendix G, Supplement 1), the fuel economy sensitivity for axles ratio changes is -0.22 (i.e., a 10 percent axle ratio increase decreases fuel economy by 2.2 percent). The fuel economy sensitivity for displacement changes without changing the number of cylinders is -0.35 (i.e. a 25 percent change in displacement decreases fuel economy by nine percent, including the effect of increased engine weight). Substituting a V-6 for a 4-cylinder or a V-8 for a V-8 significantly increases the vehicle weight, and a fifty percent HP increase decreases fuel economy by about 25 percent.

A non-linear equation that captures these effects is given by

$$\begin{aligned} \Delta FE &= -0.22\,\Delta HP - 0.56\,\Delta HP^2 \;; \quad \Delta HP > 0 \\ &= -0.22\,\Delta HP + 0.56\,\Delta HP^2 \;; \quad \Delta HP < 0 \end{aligned} \tag{1}$$

where both ΔHP and ΔFE are expressed as *percent changes*. The equation is valid for ΔHP values between 0 and 60 percent.

Attachment 2: Alternative Fuel Vehicle Model

Data Input Sources and Extrapolation Methodology

INTRODUCTION

This Attachment documents the AFV database used in the National Energy Modeling System Transportation Sector Model. The database includes the present values and forecast methodologies of six attributes for three classes of light-duty vehicles. These attributes apply to sixteen vehicle-technology types and three scenarios for nine regions of the United States.

DEFINITIONS

The vehicle classes are:

1. Small light-duty
2. Medium light-duty
3. Large light-duty

The attributes are:

1. Purchase price (1990$, including the NPV of periodic battery and fuel cell replacements)
2. Fuel Operating Cost (1990$/MMBtu)
3. Fuel Availability (Fraction of stations)
4. Vehicle Efficiency (Miles/MMBtu)
5. Emissions (impact-weighted index to gasoline in each year)
6. Vehicle Range (miles between refueling)

The vehicle-technology types are:

1. Gasoline
2. Methanol Flex
3. Methanol Neat
4. Ethanol Flex

5. Ethanol Neat
6. CNG
7. LPG
8. Electric
9. Electric Hybrid - Large ICE
10. Electric Hybrid - Small ICE
11. Electric Hybrid Gas Turbine
12. Gas Turbine Gasoline
13. Gas Turbine CNG
14. Fuel Cell Methanol
15. Fuel Cell Hydrogen
16. Diesel

OTHER TECHNOLOGIES

There are two limitations in the database in terms of other technologies. The technologies that could have been included in the database but were not are:

- hydrogen i.c.e.-- near-conventional engines that burn hydrogen as opposed to electrochemical generation of power in fuel cells (as was considered in the database). Hydrogen-burning engines have been manufactured for some time and outperform gasoline engines in terms of emissions. As with fuel cells, their main drawback is fuel price, as tremendous amounts of energy are needed for the production of hydrogen from water.

- hydrogen-CNG mix (hythane)-- also burned in i.c.e.'s and already in use. Offers great advantages in terms of emissions at a more reasonable price than pure hydrogen.

The technologies in the database that are misspecified are:

- Fuel cells/hydrogen & methanol-- at this early stage of development it would be more practical to consider these two as one technology. Each rely on essentially the same power train and electrochemical energy conversion technology, the only difference being the way the fuel is stored. Hydrogen is extremely unwieldy due to its low mass, which means that to fit in a fuel tank of manageable size it must

be liquified or bonded to other substances. Methanol, with its high hydrogen content, falls within the latter category as the hydrogen in it is the only participant in the electrochemical conversion.

APPROACH

The approach to the database development is as follows:

1. Identify data sources in the open literature and through industry contacts.

2. Obtain the data and organize it for use in the database.

3. Define and design the database to characterize the data usefully.

FORECASTING METHOD

The data base is provided in a spreadsheet format. The basic forecasting method is to identify current values for fuel prices, vehicle prices, fuel availability, etc. and one or more forecast values. The current data are entered in the 1990 column of cells for each attribute and extrapolated exponentially to and through the other data points. (In some cases, the 1990 values are assigned so that the curve fit through the 1992 values is based on 1992 actual data.) Each of the eight sections for vehicle attributes contains a detailed log of relationships and data sources.

DATABASE LIMITATIONS

Three main types of limitations apply to the database and to its usage within a transportation choice model. They are discussed below.

GENERAL DATA AND MODELING ISSUES

- Model and data do not distinguish fleet and non-fleet users. Fleet criteria include the availability of a central station, set and known use patterns, large cargo requirements (taxi, delivery, etc.), longer permissible refueling times, and limited

luxury features. Non-fleet users need public stations, much longer range, luggage space, luxury features, better performance, and higher reliability. These markets are on different legislative paths and ATF adoption schedules. They cannot be mixed and cannot be modeled using the Bunch approach.

- Model and data do not recognize non-economic forces currently distorting markets. In 1991, SAIC contacted the owners of every CNG vehicle refueling station in the country. We found that the number and use of CNG vehicles is exaggerated by about 200% and that current usage patterns and interests by non-utility users are biased by artificially low-cost CNG (e.g., no compression costs). Moreover, many of the public refueling stations have very limited refueling capability. These stations are operated mostly as demonstrations rather than as commercial stations. A similar deficiency exists at the LPG outlets, most of which are not equipped to refuel vehicles. The Bunch approach, which is geared to open-market, non-fleet purchase decisions, requires an accurate and economic (i.e., non-interventionist) baseline tied specifically to private vehicles. This baseline does not exist.

- Model specifies six decision variables cited in Bunch. SAIC work suggests that actual technology choice depends on additional variables. The following variables omitted from the model significantly affect consumer choice: reliability, maintenance cost, certainty of maintenance availability, salvage or resale value, performance, utility (trunk space in CNG vehicles, A/C in electric vehicles, etc.), safety issues (real or perceived), ease of refueling, and refueling time. A few of these omitted variables appear in other work by the Transportation Modeling committee but were not requested of SAIC. The omission of these variables is highly significant when large differences exist but are not well-understood by survey participants (e.g., 5-minute refueling for gasoline vs. 8-hour refueling for electric).

MACROECONOMIC ISSUES

The database model is generally optimistic about the current rate of technological progress and innovation and assumes it will continue to grow progressively faster. Limitations in the database suggest that these forecasts may be overly optimistic in a macroeconomic sense.

- Diversion of Resources — the diversion of government and private sector resources toward alternative investments is not considered, i.e., large sums could

go into infrastructure and mass transportation systems that are more efficient than any passenger vehicle alternative.

- Institutional Barriers — the created interests of significant economic or political actors, or groups of actors, could override market considerations for the benefit or detriment of any alternative technology or fuel.

- Environmental Barriers — one or more AFVs may receive significant opposition or backing purely for its environmental impact; moreover, public opinion as well as the environmental movement's preferences may shift in the near future, i.e., the environmental movement currently supports methanol-fueled vehicles, but that could change if a cleaner way to produce hydrogen for hydrogen-burning vehicles was found.

- Psychological Barriers — acceptance by the public is also a function of misperceptions and psychological factors, e.g., CNG, LNG, LPG and hydrogen may be perceived as dangerous to handle and thus avoided even if their safety records are objectively similar to that of gasoline.

- Information Barriers — accurate data do not exist for most of the exotic vehicle-fuel combinations (fuel cells, hybrid electric, etc.). Also cost and performance estimates for many of the emerging alternatives, especially electric vehicles, differ by a factor of 2-10 from source to source. In many cases, there is no clear basis for distinguishing among such inconsistencies.

DESCRIPTION OF VEHICLE TECHNOLOGIES

The AFV module currently analyzes 15 alternative-fuel technologies against a single conventional gasoline powered vehicle[1] in the spreadsheet analysis. Additional conventional and non-conventional technologies can be added to the analysis; however, for simplicity, conventional technologies are represented as a single category. This section of the report describes the characteristics of the alternative-fuel technologies as well as the criteria used in selection of alternative fuel-vehicle types.

[1] This study assumes all gasoline powered internal combustion engines under a single technology category even though there is significant variation within gasoline fueled engines.

Four primary technology selection criteria are employed for this study. The four criteria are the following:

- Vehicle operates utilizing a non-gasoline fuel or a significantly new engine technology.
- Technology holds the potential to penetrate the light-duty vehicle market by the year 2030.
- Technology possesses distinct fuel use, performance and/or cost characteristics relative to all other technologies considered.
- Data is available on important attributes for the vehicle technology.

Variations within each technology class based on vehicle subclass are not being analyzed as a distinct category but are incorporated into the collective category for the technology[2]. Future work in estimating market share growth for alternative-fuel technology may breakdown technology classes by engine and combustion technology; however, the complexity of such an analysis is unwarranted at the present time.

This study has identified 15 alternative-fuel technologies which have met the four criteria previously stated. Conventional gasoline technology has been grouped into one single category using average vehicle attributes taken across all conventional vehicles. Following is a list of the sixteen vehicle technologies incorporated in this study. The advantages and disadvantages of each of the individual technologies will be briefly described in the following sections.

Gasoline Internal Combustion Engine Vehicles

Presently, the vast majority of transportation vehicles utilize an internal combustion engine (ICE) which was first patented in 1876 by Nikolaus Otto. The ICE is a heat driven engine which operates by mixing air and fuel vapor together, compressing the fuel mix in a cylinder, and igniting the fuel mix by means of an electric spark. The ignited fuel mix pushes a piston which in turn drives the vehicle[3]. Since the invention of the internal combustion engine the primary power source has been gasoline, although, many other fuels such as alcohols, natural gas and diesel can be utilized. It is speculated that if the discoveries of enormous petroleum deposits in Texas had not occurred during the early development years, the automobile would have developed as an alcohol vehicle rather than gasoline.

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[2] Significant variations exist in the gasoline powered technology such as fuel injected engines versus carbureting engines; however, for simplicity all technologies utilizing a single fuel mix will be categorized together.

[3] Glasstone, S., *Energy Deskbook*, Van Nostrand Reinhold Company, New York, 1983, pp. 364-368.

One of the primary advantages of conventional ICE vehicles is that economically these vehicles are inexpensive to operate due to the large development and refining infrastructure established for petroleum products. An abundance of petroleum deposits occur throughout the world and transportation of petroleum is not difficult in comparison to methanol and natural gas.

The conventional gasoline ICE vehicles are more harmful to the environment than the majority of alternative-fuel vehicles. Environmental concerns is one of the leading incentives for the development of alternative-fuel vehicles due to the problems associated with greenhouse gasses and urban ozone formation problems.

Diesel Vehicles

The diesel engine, like the gasoline engine, is an internal combustion engine which is heat driven from the ignition of diesel fuel in the cylinder which in turn drives the pistons. Unlike the gasoline ICE, a spark plug is not used to ignite the fuel mix but rather the combination of the compression and heat of the cylinder causes ignition of the fuel mix.

Ethanol Vehicles

Ethanol is a fuel which is currently being used to supply ethanol powered vehicles in a ratio of approximately 85 percent ethanol to 15 percent gasoline as well as a gasoline supply extender for conventional gasoline powered engines in a ratio of approximately 5 percent ethanol and 95 percent gasoline. This study is considering only ethanol vehicles (vehicles using the 85/15 percent mix) as a category separate from conventional vehicles. Two technology categories exist under the ethanol fuel heading. Ethanol Neat Vehicles which use only ethanol fuel and Ethanol Flex Vehicles which have the ability to switch between gasoline and ethanol fuels.

Ethanol can be produced from food sources such as corn and sugar cane or from non-food biomass such as trees, grass, waste paper, and cardboard. Presently, approximately 95 percent of ethanol fuel being produced in the United States comes from corn. Neat ethanol engines are expected to produce a 30 percent increase in efficiency over conventional gasoline engines; however, ethanol fuel has a lower energy content of only 67 percent of gasoline. A variation in cost estimates for ethanol fuel production exist depending on the source material and the distillation process. The EPA estimates that the "gasoline equivalent" ethanol price using corn

stock is between $1.47 and $2.07 per gallon[4].

Ethanol fuel provides several important environmental benefits over gasoline in both the consumption and production stages. Ethanol is produced from a renewable energy source such as corn or sugar cane, where as petroleum is a non-renewable energy source which could be depleted in the future. Ethanol fueled vehicles emit a lower amount of carbon dioxide, nitrogen oxide and hydrocarbons than gasoline[5]. The Environmental Protection Agency estimates that carbon dioxide emissions, the major component of "greenhouse gases", are reduced to zero using ethanol produced from corn or sugar cane when considering the carbon reabsorption factor of corn during the growing stage[6].

Methanol Vehicles

Methanol fuel is similar in some respects to ethanol since it also is used as a gasoline extender in conventional gasoline engines and as a fuel in methanol engines. Presently methanol is mixed with gasoline in an 85 percent methanol/ 15 percent gasoline (M85) ratio and is consumed in a methanol engine. Two technologies exist for this analysis under the methanol heading; Methanol Neat which operates on M85 and Methanol Flex which has the ability to switch between M85 and gasoline depending on economic and availability factors.

Currently natural gas is the primary source of methanol although other materials such as coal, biomass and cellulose can be used. Methanol allows countries with excess natural gas supplies to export fuel without the expense of pipelines and LNG process. It is estimated that the wholesale price of methanol produced from natural gas is approximately $.40/gallon. However, because methanol has only about one half of the energy per gallon of gasoline, the cost per gasoline equivalent gallon is estimated at $.75[7].

Environmental advantages of methanol fueled vehicles are reductions in ozone formation, volatile

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[4] Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Ethanol as an Automobile Fuel*, April, 1990, pp. 15-22.

[5] The Gas Research Institute, The Energy Information Administration, and Science Applications International Corporation, *Identification and Analysis of Factors Affecting the Adoption of Alternative Transportation Fuels*, 1991, pp. 20-21.

[6] Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Ethanol as an Automobile Fuel*, April, 1990, pp. 49-50.

[7] The Gas Research Institute, The Energy Information Administration, and Science Applications International Corporation, *Identification and Analysis of Factors Affecting the Adoption of Alternative Transportation Fuels*, 1991, p. 28.

organic compounds (VOC) and "greenhouse gas" emissions[8]. Ozone formation is a significant problem in urban areas linked to the emission of gasoline vehicles. Methanol emissions produce a lower photochemical reactivity than gasoline emissions; therefore, reducing the urban ozone formation problem. It is estimated that methanol vehicles emit 80 percent less VOC emissions than gasoline vehicles. Methanol vehicles emit increased volumes of formaldehyde and methanol gas which can be harmful in concentrated amounts. Further research is being conducted on the health risks associated with methanol and formaldehyde emissions.

Electric Vehicles

Extensive alternative fuel vehicle research is now being done to improve electric vehicle performance. The primary obstacle of electric car development is battery technology. Various automobile manufacturers and research groups are concentrating on improving battery capabilities; however, at the present time battery technology limits electric vehicle range and performance attributes. For this reason electric vehicle motors have been combined with other conventional and non-conventional technologies in order to enhance vehicle performance. Technologies combined with electric motors include the internal combustion engine and gas turbine engine. This study will consider four technologies under the electric vehicle heading; electric, electric hybrid, electric hybrid/small ICE, and electric hybrid/gas turbine.

The primary advantage of electric-powered vehicles is that they produce virtually no direct emissions at the point of consumption. Direct emissions produced by electric vehicles are largely hydrogen emissions released during the battery recharging stage. Although hydrogen is an explosive emission in high concentration, hydrogen poses no problem to atmospheric air pollution[9]. While electric vehicles produce almost no direct emissions there are emissions associated with the electricity production stage depending on the power source of the electricity generation. Centralized power plants located away from urban centers eliminate urban ozone formation problems and can effectively control emissions associated with fossil fuel consumption. Electric motors have the advantage over internal combustion engines (ICE) because electric motors do not idle when the motion is stopped as ICEs do thus eliminating the idling power loss which can be significant in urban transportation settings.

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[8] Energy Protection Agency, *Analysis of the Economic and Environmental Effects of Methanol as an Automobile Fuel*, April, 1990, pp. 15-18.

[9] The Gas Research Institute, The Energy Information Administration, and Science Applications International Corporation, *Identification and Analysis of Factors Affecting the Adoption of Alternative Transportation Fuels*, 1991, p. 21.

Considering present electricity prices, exclusive electric vehicles as an alternative to gasoline vehicles are not as cost effective as ethanol, methanol, and natural gas vehicles. Even though electricity as a transportation fuel delivers 50 percent more miles per Btu than other fuels, the current price of electricity makes electric fuel transportation notably more expensive than conventional vehicles[10].

Compressed Natural Gas/Liquid Petroleum Gas Vehicles

Compressed Natural Gas (CNG) and Liquid Petroleum Gas (LPG) vehicles are grouped together in this summary because the engine technology is similar for the two vehicles utilizing different fuel sources. CNG vehicles have been in use for several decades in the United States while in other parts of the world they have been in operation since the 1930's[11]. The largest application of CNG vehicles has been in heavy-duty fleet vehicles because of the bulky natural gas storage tanks.

The CNG/LPG technology consists of a modified internal combustion engine connected to the fuel source in a closed system[12]. Because the fuel supply is in a gaseous state the entire storage engine system must be a closed system which eliminates the emissions problem of evaporating fuel during storage and refueling. The CNG/LPG engine produces higher thermal efficiencies than conventional gasoline engines; however, because of the additional weight involved with the fuel storage tanks the additional energy efficiencies are almost negated[13]. However; presently it is reported that natural gas vehicle operation is less expensive than conventional gasoline vehicles. A survey of gas utilities taken by the Gas Research Institute indicated that the CNG price per gallon-equivalent of gasoline is $.85-$1.10. GRI reports that it's analysis indicates that CNG prices including compression costs and fuel taxes are 13 percent lower than gasoline cost for conventional vehicles[14].

Compressed natural gas and liquid petroleum gas vehicles are considered clean fuel vehicles

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[10] Ibid, p.30.

[11] Environmental Protection Agency, *Analysis of the Economic and Environmental Effects of Compressed Natural Gas as a Vehicle Fuel*, Volume II Heavy-Duty Vehicles, April 1990, pp. 1-2.4.

[12] Energy Information Administration, *Energy Consumption and Conservation Potential: Supporting Analysis for National Energy Strategy*, December 21, 1990, pp. 90-91.

[13] Energy Information Administration, *Energy Consumption and Conservation Potential: Supporting Analysis for National Energy Strategy*, December 21, 1990, pp. 90-91.

[14] The Gas Research Institute, The Energy Information Administration, and Science Applications International Corporation, *Identification and Analysis of Factors Affecting the Adoption of Alternative Transportation Fuels*, 1991, p. 29.

because the fuel burns cleaner than conventional gasoline vehicles. Natural gas vehicles do not emit ozone formation emissions, however, these vehicles do emit a high amount of NO_x and methane which is an important contributor to greenhouse gases.

Gas Turbine Vehicles

Gas turbine engines have been in existence for several decades and presently have several significant applications such as aircraft engines and electricity generation. Gas turbine technology is a significant variation from ICE technology. A gas turbine engine consists of three principle components; a compressor which compresses outside air to be mixed with fuel, a combustion chamber where the compressed air and fuel are ignited, and turbine which is turned by the exhaust of the ignited fuel mix[15].

Gas turbine vehicles potentially could be up to 50 percent more efficient than conventional internal combustion engine vehicles[16]. The increased efficiency is due to the fact that a turbine engine utilizes a larger percentage of the work being performed by the fuel than ICE's. Small turbine engines suitable for use in transportation vehicles are not being produced now on a large scale; therefore, the current cost of turbine engines are prohibitive for vehicle use.

Gas turbine engines could be designed to burn different fuels ranging from alcohols to diesel fuel. This study will consider two technologies under the gas turbine engine, compressed natural gas and conventional gasoline.

Fuel Cell Vehicles

The concept of fuel cells as a power source for transportation vehicles is similar to electric vehicle technology because an electric current powers a motor which drives the vehicle. The difference is that an electric vehicle runs off of a battery which is recharged periodically while a fuel cell is charged by a separate power source such as methanol or hydrogen. The first large scale applications of fuel cell technology were the Apollo and Gemini space missions which sparked interest in fuel cell technology in vehicle transportation.

Fuel cell technology has the advantage of higher conversion efficiency from the fuel source into

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[15] Glasstone, S. *Energy Deskbook*, Van Nostrand Reinhold Company, New York, 1983, pp. 152-156.

[16] Energy Information Administration, *Energy Consumption and Conservation Potential: Supporting Analysis for National Energy Strategy*, December 21, 1990, pp. 90-91.

electricity than a combustion engine. A large portion of the energy derived in a heat driven internal combustion engine is lost in the form of external heat which does not occur in the fuel cell technology. Fuel cell technology remains in the development stage and cost projections of transportation vehicles are extremely high. Further research may lower the costs of fuel cell technology; however, for now fuel cell technology seems unrealistic for large scale adoption.

VEHICLE PRICES

This section documents vehicle purchase prices in the database. The output of the database is a vehicle price for sixteen technologies for three vehicle sizes and three penetration scenarios, from 1990 through 2030, in thousands of 1990 dollars.

The general approach is to establish current and ultimate price premia for AFV's (alternative fuel vehicles) over the price of a gasoline I.C.E. (internal combustion engine) vehicle, and to use an exponential decay function (expressed as a compound percentage decline rate) to project each price premium towards its ultimate value. The shape of the curve implied by the price decay is based on forecasted future price levels or SAIC's judgment where no data are available. A non-fuel escalation rate was used to establish future prices of gasoline vehicles for each of three vehicle sizes (small, medium, and large)[17] through the year 2030.

Vehicle prices were obtained from the following inputs:

- Current price of gasoline vehicles by size (S, M, L).
- Current price premia for 15 other vehicle types independent of size (i.e., fuel-related premium or discount to base gasoline vehicle).
- Ultimate long-run price premia for 15 other vehicle types independent of size.
- Non-fuel escalation rate independent of vehicle type.

[17] Size categories are defined primarily by weight, and secondarily by passenger cabin volume. These definitions are consistent with usage in all of the literature, and in terms of weight are: below 2600 lbs for small vehicles, between 2600 and 3200 lbs for mid size, and above 3200 for large.

- Annual, compound percentage decline in current premium towards ultimate premium, or premium decay, for 15 vehicle types for three scenarios (B, H, L).

The approach has the following advantages:

- Projected AFV prices should be relatively consistent vis a vis conventional gasoline and other AFV prices.

- Incorporating the price of gasoline vehicles into AFV prices ensures that the non-fuel escalation rate is taken into account for all technologies.

- Updating and revising figures based on future developments are facilitated.

CURRENT VEHICLE PRICES

Determining current vehicle prices required two steps: finding the price for gasoline vehicles of three sizes (small, medium, and large), and obtaining current AFV purchase prices by adding a premium to the gasoline vehicle price for each technology.

GASOLINE VEHICLE PRICES

Prices for gasoline vehicles were established by averaging the prices of three representative vehicles for each size category. The vehicles were selected on the basis of market share[18]. All prices are manufacturer's suggested retail prices obtained from the National Automobile Dealers Association (NADA) used vehicle price guide. Table F-5 below provides detailed information on the selected gasoline vehicles.

[18] Market share source: NADA, August 1992, p.32.

Table F-5. Gasoline Vehicle Characteristics (1990)

SIZE	VEHICLE MAKE, MODEL, BODY & STYLE	PRICE (1990 $)	WEIGHT (LBS)
LARGE	Ford Ltd Crown Victoria V8/ 4D Sedan	$17,257	3821 lbs
	Cadillac DeVille/ 4D Sedan	$27,540	3546 lbs
	Dodge B250/ Van	$12,575	NA
MID-SIZE	Beretta Corsica/ 2D coupe GT2	$13,750	2839 lbs
	Ford Taurus/ 4D sedan, GL	$13,834	3089 lbs
	Honda Accord/ 4D sedan LX	$14,895	2857 lbs
SMALL	Honda Civic/ 3D hatchback DX	$8695	2165 lbs
	Chevrolet Cavalier L4/ 4D sedan	$8820	2471 lbs
	Ford Escort/ 2D hatchback LX	$7806	c2312 lbs

Sources for price and weight:

Large: (NADA, July-August, 1992, ps.23, 75, 271)
Mid-sized: (NADA, July-August, 1992, ps.29, 74, 174)
Small: (NADA, July-August, 1992, ps.29, 73, 173)

CURRENT PRICE PREMIA FOR AFV'S

Current price premia are the premia paid in the market today over conventional gasoline vehicle prices for each technology in the database. All current AFV prices are calculated by adding these premia to the current gasoline vehicle price values for each category. The premia are added to the current gasoline vehicle price to obtain the current AFV prices for each vehicle size, type, or scenario. All premia and SAIC's assumptions, rationales, and comments for each technology are provided below. Each entry also contains the citations consulted by SAIC; abbreviations are more fully defined at the end of this report.

- **Diesel — $1000.** Average premia for representative diesel passenger vehicles; figure was slightly higher in the past.
  Sources: (NADA, July-August, 1992 & SAIC).

- **Ethanol Flex — $4,500.** Figure was set at the upper end of the range in the literature because of recent DOE data that places a much higher premium on flexible fuel vehicles.

Sources: FFV range $2000-5000 (Cogan, August 1992, p.94); average of $6,400 for DOE AFV's (including ethanol, methanol and CNG) procured in 1990 (G.A.O, May 1991, p.20).

- **Ethanol Neat — $2000.** As is the case with ethanol flex, estimate is at the upper end of the range to make it more consistent with recent DOE data.
  Sources: $300-2000 (Cogan, August 1992, p.94), DOE AFV's data (G.A.O., May 1991, p.20).

- **Methanol Flex — $4,700.** Premium is equal to that of ethanol flex plus $200 for higher manufacturing costs due the corrosive nature of the fuel, i.e., stainless steel or specially treated materials are needed for the engine. Figure is consistent with the literature consensus and recent DOE data.
  Sources: Fully optimized vehicle not engineered yet (CRS, 1989, p.17); higher corrosiveness (Rouse, 1991).

- **Methanol Neat — $2,200.** Premium is equal to that of ethanol neat plus $200 for higher manufacturing costs due the corrosive nature of the fuel, i.e., stainless steel or specially treated materials are needed for the engine. Figure is consistent with the literature consensus and recent DOE data.
  Sources: $2000 1992 Ford econoline van (NREL, 1992); FFV range $2000-5000 (Cogan, August 1992, p.94); average of $6,400 for DOE AFV's (includes ethanol, methanol and CNG) procured in 1990 (G.A.O, May 1991, p.20); $210-340 by 1995 (D.O.E., August 1990, p.ix); higher corrosiveness (Rouse, 1991).

- **Electric — $45,000.** This figure includes an estimate of the net present value of battery replacements. It is consistent with most recent sources and manufacturer-quoted prices of soon-to-be released vehicles.
  Sources: 1989 GM G vans priced at $32,500 in 1989 (SAIC/report, 1991, p.25); 1993 Ford small van priced at $100,000 (NREL, 1992, on-line); batteries premium $6,000 by 1995; 1993 GM Impact production cost range $15-20,000 (O.T.A., 1990, p.119); GM Impact price range $20,000-30,000 (Woodruff, 1991, p.58); batteries premium $2,600-8,200 for advanced lead-acid battery (ICAMF, 1990, 1.16); Fiat Electra priced at $22,000 or twice the price of its I.C.E. twin (Woodruff, 1991, p.57); current battery price $1,500, replaced every 20,000 miles (Woodruff, 1991, p.58).

- **Electric Hybrid/Large I.C.E. — $50,000.** Figure includes the price of a regular electric vehicle (EV) plus a premium for the large I.C.E. The premium accounts for the fact that two engines would be costly and inefficient in terms of maintenance and use of space. A large I.C.E. acts as a range extender in the same way as a conventional gasoline I.C.E. The difference in price between a small and large I.C.E. is deemed to be insignificant at any stage. The figure is consistent with manufacturer prices of soon-to-be released vehicles and the consensus of the literature.
  Sources: 1993 Ford small hybrid van priced at $100,000 (NREL, 1992, on-line); high cost of adding batteries and electric motors to the engine of an I.C.E. (Woodruff, 1991, p.59).

- **Electric Hybrid/Small I.C.E. — $50,000.** See Electric Hybrid/Large I.C.E. above. A small I.C.E. only serves as a generator to recharge the batteries for the electric engine to operate. The difference in price between a small and large I.C.E. is insignificant at any stage.
  Sources: 1993 Ford small hybrid van priced at $100,000 (NREL, 1992, on-line); high cost of adding batteries and electric motors to the engine of an I.C.E. (Woodruff, 1991, p.59).

- **Electric Hybrid/Turbine — $125,000.** Figure includes the price of an electric hybrid/I.C.E. plus a high premium that reflects the absence of a viable prototype at this time. Gas turbine vehicles were manufactured in the fifties without success due to lack of competitively-priced, heat-resistant materials; however, new developments may solve such obstacles and a prototype vehicle may be successfully produced by 1998.
  Source: (The Economist, September 28, 1991).

- **CNG — $2,750.** Although some economies of scale are already present, all CNG vehicles are essentially retrofitted rather than optimized, therefore a significant premium (and potential for improvement) remains. The selected figure is consistent with the middle to the higher end of the 1992 literature ranges.
  Sources: Range of $2000-5000 (Cogan, August 1992, p.94); 1992 Chrysler Dodge B-Series Van Wagon $5000 (NREL, 1992, on-line); $2,550-3,250 (EPA, 1990, p.10); $2550-3250 for light-duty automobile (large), $1650-2250 (small-medium), $2350-3050 light duty truck; mass-produced dual-fuel $1600 (ICAMF, 1990, p.5.7); average of $6,400 for DOE AFV's (includes ethanol, methanol and CNG)

procured in 1990 (G.A.O, May 1991, p.20); $800 by 1995 (D.O.E., August 1990, p.ix).

- **LPG — $1,500.** Although some economies of scale are already present, all LPG vehicles are essentially retrofitted rather than optimized, therefore a significant premium (and potential for improvement) remains. The selected figure is consistent with the middle to the higher end of the 1992 literature ranges.
  Sources: $1,200-2,200, (ICAMF, 1990, p.1.15.); 1992 Ford F-700 medium duty truck conversion option at $800 (NREL, 1992, on-line).

- **Turbine/Gasoline — $125,000.** Figure includes a high premium that reflects the absence of a viable prototype at this time. Gas turbine vehicles were manufactured in the fifties without success due to lack of competitively-priced, heat-resistant materials; however, new developments may solve such obstacles and a prototype vehicle may be successfully produced by 1998. The figure is consistent with the electric hybrid/turbine vehicle premium. No significant estimated price differential between CNG and gasoline technologies at this time.
  Source: (The Economist, September 28, 1991).

- **Turbine/CNG — $125,000.** See Turbine/Gasoline above. No significant estimated price differential between CNG and gasoline technologies at this time.
  Source: (The Economist, September 28, 1991).

- **Fuel Cell/Hydrogen — $150,000.** Figure includes a high premium for fuel cells because they are far more expensive than conventional batteries; there is also a premium included for fuel storage. Production prices in the literature diverge widely. Both hydrogen and methanol technologies rely on hydrogen for their electrochemical reactions and differ only in the way it is stored, i.e., as a component of methanol, or independently; therefore, no significant difference between them exists at this stage. Hydrogen-burning (as opposed to fuel cell) vehicles are far more feasible and less costly at this time.
  Sources: Fuel cells cost and premium for fuel storage (McCosh, 1992, p.29); 1995 prototype's price: drive system and engine $225,000, plus a fuel storage tank with a price range of $2,253 to $7,709, for a subtotal of $225,203 to $232,659 not including chassis (C.E.C., June 1991, pp.25-30).

Hydrogen I.C.E. Sources: feasibility; prototypes in Japan, i.e., Nissan's joint effort

with Musashi Institute of Technology (Maruyama, 1991); Mazda hopes to sell a few hydrogen-burning cars in California within ten years; current models are not optimized; premium for hydrogen tank is $26,000 (Templeman, 1991, p.59).

- **Fuel Cell/Methanol — $150,000.** See Fuel Cell/Hydrogen above. Both hydrogen and methanol technologies rely on hydrogen for their electrochemical reactions and differ only in the way it is stored, i.e., as a component of methanol, or independently; therefore, no significant difference between them exists at this stage.
  Sources: See Fuel Cell/Hydrogen.

FUTURE VEHICLE PRICES

Ultimate price premia are defined as the minimum future price differentials between gasoline and ATF vehicles. An extensive literature search and SAIC's own resources yielded forecast future prices, which were used to set ultimate price premia and the approximate expected year they will be reached. All ATF vehicle prices falling between the ultimate and the current price premia are calculated by using the price premia decay rate described in the subsequent section.

FUTURE GASOLINE VEHICLE PRICES

For all gasoline models, the prices beyond 1992 escalated at 2% per year. Non-fuel escalation factors include:

- The historical tendency of options to become standard equipment through time.

- Progressively higher additional costs for emissions controls and efficiency requirements. These are estimated to be $70 for a TLEV and $170 for LEV/ULEV (CARB, August 1990, p.IX.13).

- Increased investment in more efficient, lighter engines such as the 2-stoke engine (The Economist, September 28, 1991) and higher cost super-light body materials such as carbon composites (GM, 1992, pp.14,15).

DEVELOPMENT OF ULTIMATE PRICE PREMIA

Minimum price differentials are reached once all criteria for improvement relative to conventional prices have been met. The criteria include the maximization of well-known economic principles such as economies of scale, returns to scale, and learning curves. The future year and value assigned to AFV premia were found by applying the above criteria to the current status of the technology, the short-term and future projected gains, and relevant theoretical limitations.

Once values for ultimate cost and associated year were calculated, the premia were added to the corresponding year's conventional gasoline price. After an AFV has reached its ultimate premium, price differentials between that AFV and a conventional vehicle remain constant except for non-fuel escalation. Assumptions, rationales and comments for each technology are provided below.

- **Diesel — $1,000.** Average premia for representative diesel passenger vehicles; figure was slightly higher in the past, but is not expected to decline further.
  Sources: (NADA, July-August, 1992 & SAIC).

- **Ethanol Flex — $0.** Near-zero ultimate price premium assumes economies of scale and optimization achieved prior to switch to ethanol neat vehicles. Figure consistent with EPA and most recent literature.
  Source: (EPA/ethanol, 1990, Appendix C, p.2).

- **Ethanol Neat — $0.** Near-zero ultimate price premium assumes economies of scale and optimization of both ethanol types. Prior development of flex vehicle would provide learning curve feedback. Figure consistent with EPA and most recent literature.
  Source: (EPA/ethanol, 1990, Appendix C, p.2).

- **Methanol Flex — $200.** Premium is equal to that of ethanol flex plus $200 for higher manufacturing costs due the corrosive nature of the fuel, i.e., stainless steel or specially treated materials are needed for the engine.
  Sources: Premia for corrosion-resistant materials, fuel sensing and control systems, and larger fuel tank for a total range of $150-500 in the late nineties, down to near-zero premium after that (CRS,1989,p.17); $150-300 at high volume production (EPA, April 1990, p.35); $300 with large scale production (ICAMF, 1990, p.1.14).

- **Methanol Flex — $100.** Premium is equal to that of ethanol neat plus $100 for higher manufacturing costs due the corrosive nature of the fuel, i.e., stainless steel or specially treated materials are needed for the engine. Such a premium would be smaller for a dedicated neat vehicle due to greater economies of scale, optimization, and transfer of knowledge from flexible fuel vehicles.
  Sources: (EPA, 1990, Appendix C, p.2, & CRS, 1989, p.17).

- **Electric — $6,500.** Figure includes an estimate of the ultimate price premium of a battery, assuming steady improvements in battery technology and mass production taking place as zero-emission vehicle laws take effect. Advanced batteries now in an infant stage of development could considerably extend the range of the vehicle without the need for replacement. Differences between EV and EH vehicles are unimportant, as their most expensive component, the batteries, is the same. The figure is consistent with the consensus of the literature.

  Sources: Premium for ZEV $1350 (SAIC/report, 1991, p.35); advanced batteries, such as sodium-sulfur, with a 100,000-mile life may be available by 1994 (Woodruff, 1991, p.58).

- **Electric Hybrid/Large I.C.E. — $6,500.** See Electric above. Differences between EV and EH vehicles are unimportant, as their most expensive component, the batteries, is the same. The additional cost of a range-extender I.C.E. (regardless of size) ultimately approaches zero as economies of scale, transfer of knowledge and innovation arrive. The figure is consistent with the consensus of the literature.

  Sources: See Electric above.

- **Electric Hybrid/Small I.C.E. — $6,500.** See Electric and Electric Hybrid/Large I.C.E. above. The additional cost of a range-extender I.C.E. (regardless of size) ultimately approaches zero as economies of scale, transfer of knowledge, and innovation arrive. The figure is consistent with the consensus of the literature.
  Sources: See Electric Hybrid/Large I.C.E. above.

- **Electric Hybrid/Turbine — $6,500.** See Electric above. Differences between EV and EH vehicles are unimportant, as their most expensive component, the batteries, is the same. The additional cost of a range-extender turbine ultimately approaches zero as economies of scale, transfer of knowledge, and innovation

arrive. The figure is consistent with the consensus of the literature.
Sources: See Electric Vehicle above, and Turbine/Gasoline & CNG below.

- **CNG — $750.** Assumes mass-production of optimized dedicated vehicle. The figure is consistent with the consensus of the literature.
  Sources: $700-800 for optimized and dedicated vehicle (O.T.A., 1990, p.101); $800 for optimized large-scale production, less for dedicated vehicle (ICAMF, 1990, p.1.14).

- **LPG — $500.** Assumes mass-production of optimized dedicated vehicle. The figure is consistent with current price differences between LPG and CNG vehicles, and assumes such differences will persist.
  Source: $500 (SAIC judgment).

- **Turbines/Gasoline — $1,500.** Assumes likely advances in high temperature ceramics and electronic combustion controls will take place by the end of the decade and eventually make this technology cost-competitive with conventional technology.
  Source: (The Economist, September 28, 1991, p.95).

- **Turbines/CNG — $1,500.** See Turbine/Gasoline above. Assumes there will be no significant price differential between CNG and gasoline technologies.
  Source: (The Economist, September 28, 1991, p.95).

- **Fuel Cell/Hydrogen — $6,500.** Assumes significant advances in storage technology and fuel cell manufacturing are accomplished due to high demand.
  Sources: storage technique breakthroughs: liquid hydrogen, or hydrogen bonded with powdered metals or stored in metal alloy balls may render it as safe as gasoline (Templeman, 1991, pp.59, 60); by 2010 the fuel cell hybrid will be $6,562 plus chassis (C.E.C., June 1991, pp.25-30).

- **Fuel Cell/Methanol — $6,500.** Assumes significant advances in storage technology and fuel cell manufacturing are accomplished due to high demand.
  Sources: Hydrogen-rich methanol would allow a fuel cell vehicle to refuel as rapidly as an I.C.E. vehicle (Economist, September 1991, p.75); storage technique breakthroughs: liquid hydrogen, or hydrogen bonded with powdered metals or stored in metal alloy balls may render it as safe as gasoline (Templeman, 1991,

pp.59, 60); by 2010 the fuel cell hybrid will be $6,562 plus chassis (C.E.C., June 1991, pp.25-30).

A comparison of the current and ultimate price premia discussed above is provided in the following table.

Table F-6. AFV Price Premia by Technology

TECHNOLOGY	PRICE PREMIA	
	CURRENT	ULTIMATE
Diesel	1,000	1,000
Ethanol Flex	4,500	0
Ethanol Neat	2,000	0
Methanol Flex	4,700	200
Methanol Neat	2,200	100
Electric	45,000	6,500
Electric Hybrid/Large ICE	50,000	6,500
Electric Hybrid/Small ICE	50,000	6,500
Electric Hybrid/Turbine	50,000	6,500
CNG	2,750	750
LPG	1,500	500
Turbine/Gasoline	125,000	1,500
Turbine/CNG	125,000	1,500
Fuel Cell/Methanol	150,000	6,500
Fuel Cell/Hydrogen	150,000	6,500

APPLICATION OF THE DECAY FUNCTION

This rate is the annual, compound percentage decline in the current premium towards the ultimate premium for all AFV technologies. AFV prices are assumed to fall along a curve between the current and the ultimate price premia. The curve's shape is determined by the decay rate. If the

exponential decay rate is rapid, the vehicle price reached its ultimate price well before 2030 (e.g., ethanol and methanol). If the decay rate is slow, the ultimate price may not be reached in the 40-year period.

Table F-7. LDV and AFV Cost Decay Rates

FUEL TYPE	LOW	BASE	HIGH	EXPLANATION
Diesel ICE	10%	1%	1%	Diesel engines are advantageous only for medium and heavy-duty vehicles. Unsuccessful previous attempt to penetrate the passenger car market.
Ethanol & Methanol Flex	5%	10%	15%	Similar technologies are assumed to have near identical decay rates and constitute the alcohols flexible fuel market segment. Because of initial fuel availability advantages over neat vehicles and already existing technology (retrofitted gasoline engines), flex ones are expected to be mass-produced much sooner than optimized neat vehicles. Consistent with the consensus of the literature.
Ethanol & Methanol Neat	2.5%	5%	7.5%	Because optimized neat vehicles necessitate more engineering, they will take longer to develop and be mass-produced than flex vehicles. It is assumed that there will be a trend towards optimization and that flex vehicles will not be available in significant numbers by the end of the next decade. The rates were rounded off to figures equal to half of those for flex vehicles and are consistent with the consensus of the literature.
Electric & Electric Hybrids (ICE & Turbine)	7.5%	12.5%	15%	Assuming steady improvements in battery technology and the expansion of zero emissions state limit programs, the overall advantages of electric and hybrid vehicles will translate into the fastest annual increase in production for any AFV. The rates seem even faster because initial production is much lower than other competing technologies, i.e., CNG, LPG, and alcohol flex.
CNG	5%	10%	15%	Assuming retrofit conversion through 2000; dedicated mass-produced optimized vehicle after that year.
LPG	2%	4%	6%	Dedicated mass-production will come later than CNG vehicles, due to the latter's greater advantages vis a vis the non-fleet passenger vehicle market segment.
Turbines: Gasoline & CNG	5%	10%	15%	Rates consistent with, and slightly lower than, those for electrical vehicles. Both technologies are in their infancy but are also very promising. Assuming technology is operational by the end of the century, costs should decrease rapidly after that due to high initial learning curve position (e.g., turbine technology) and use of conventional fuel.
Fuel Cells: Methanol & Hydrogen	5%	10%	15%	Rates are consistent with electrical vehicles and rounded off to equal those of turbine vehicles. The development of this technology presents more obstacles than turbines but offers more potential rewards, i.e., lower emissions and seemingly limitless fuel supply.

SOURCES:

- **Diesel** — Rate tied to gasoline rate; the price premium is assumed to remain constant through time. The usefulness of this technology is limited to large vehicles.

- **Ethanol Flex** — $300 premium with large production in the future (EPA, April 1990, p.2); limited production by 1993, full by 2000 (C.E.C., 1989, p.7).

- **Methanol Flex** — Costs dropping since Chrysler began selling its Dodge Spirit and Plymouth Acclaim without a price premium, other auto makers will presumably follow (Cogan, August 1992, p.94); limited production by 1993, full by 2000 (C.E.C., August 1989, p.6); Federal fleet assumptions for cost premia: 1993=$2,500, 1994=$1500, 1995=$1000, 1996=$275, 2001=$150 (D.O.E., May 1992, p.26).

- **Methanol Neat** — No significant production for dedicated vehicles before 2007-2010 (CRS, 1989, p.17-18).

- **Electric** — Large resources from Detroit's consortium going into EV research (Woodruff, 1991); estimated manufacturing cost versus annual production volume (no. of vehicles manufactured/EV cost in 1988$): 30/$48,200, 100/$40,000, 1000/$29,500, 10,000/$21,000, 50,000/$18,100 (C.E.C., August 1989, p.6); limited production 1993-2000 (C.E.C., 1989, p.7); economies of scale after 1998 (60,000-100,000 units) and replacement of DCEV (direct current electric vehicle) by ACEV (alternating current e.v.); NiFe batteries and advanced battery use beginning 2003 and 2005 respectively, by 2009 1/2 of the EV and EV/hybrid market captured (A.F., 1990, p.18-22); GM Impact plant production will be 25,000/year (Woodruff, 1991, p.54, p.58); it takes production runs of at least 50,000/year to make a profit on a reasonably priced vehicle (Woodruff, 1991, p.59).

- **Electric Hybrid/Large I.C.E.** — NiFe battery car by 2003; by 2010 half of the EV's may be EV/hybrid (A.F., 1990, p.18-22). See other applicable references above under Electric.

- **Electric Hybrid/Small I.C.E.** — NiFe battery car by 2003; by 2010 half of the

EV's may be EV/hybrid (A.F., 1990, p.18-22). See other applicable references above under Electric.

- **Electric Hybrid/Turbine** — NiFe battery car by 2003; by 2010 half of the EV's may be EV/hybrid (A.F., 1990, p.18-22). See other applicable references above under Electric, and under Turbine.

- **CNG** — Retrofit conversion 1993-2000 (C.E.C., 1989, p.7).

- **LPG** — Retrofit conversion 1993-2000 (C.E.C., 1989, p.7).

- **Turbine/Gasoline** — (The Economist, September 28, 1991, p.95).

- **Turbine/CNG** — (The Economist, September 28, 1991, p.95).

- **Fuel Cell/Hydrogen** — Prototype vehicle by 1993, demonstration vehicle by 2000 (C.E.C., 1989, p.7); prototype by 1995 possible, limited production 1000 to 10,000 units/year by 2002 (C.E.C., June 1991, p.20); main current obstacles are safety, compact storage, and competitive production costs; factory site vehicles by 2000, road vehicles beyond that (Tyler, 1990, p.20).

- **Fuel Cell/Methanol** — See references for Fuel Cell/Hydrogen above.

VEHICLE EFFICIENCY

This section documents vehicle efficiency in the database. The output of the database is the efficiency rate for sixteen technologies for three vehicle sizes, from 1990 to 2030. The rate is given in miles per MMBtu.

The general approach consists of establishing the current mid-size vehicle mileage per MMBtu for each fuel. The mileage figures are then adjusted for differences in vehicle size (e.g., small and large) using an index of mileage by size, as a function of mid-size mileage, while holding fuel constant. A fuel-use adjustment is needed to correct the miles/MMBtu estimates for pure fuel use vs. hybrid fuel use (e.g., electric vs. electric hybrid).

To obtain future vehicle efficiency, an annual simple percentage efficiency gain by vehicle type was developed. Fuels with greater potential for engine efficiency improvements were assigned greater estimated efficiency gains over time (e.g., gasoline I.C.E. vs. EV.).

Thus, the vehicle efficiency inputs are:

- Current mileage per MMBtu for each fuel.
- Mileage by vehicle size (small, large) as a function of mid-size vehicle mileage.
- A fuel-use efficiency adjustment to correct the miles/MMBtu estimates for pure fuel use vs. hybrid fuel use.
- Annual simple percentage efficiency gain by vehicle type for all vehicle types.

The approach has the following advantages:

- Projected efficiency rates should be relatively consistent vis a vis conventional gasoline I.C.E. and other technology efficiency rates.
- Updating and revising figures based on future developments are facilitated.

CURRENT VEHICLE EFFICIENCY

This section describes the process of obtaining current efficiency rates and adjusting for size and fuel use. As explained in the previous section, current mileages per MMBtu for each vehicle technology were initially obtained for a mid-size vehicle only. The following table shows these current efficiency rates. The sources consulted and the specific references and/or figures used are given immediately after the table.[19] Efficiencies for the other two vehicle sizes were obtained by applying an adjustment factor of +10% for small, and -10% for large, to the base mid-size vehicle efficiency rate shown in the following table.

[19] Some improvements in the efficiency of gasoline vehicles also apply to AFV's, i.e., super-light materials and on-board computers, while others do not, i.e., two-stroke engines. Those that do apply do so differently from one technology to another, i.e., it will be easier to reduce air drag in a vehicle that has a small, powerful engine and does not require large fuel storage capacity.

Table F-8. Current Mid-Sized Vehicle Fuel Efficiencies

FUEL TYPE	Miles/MMBtu
Gasoline	265
Diesel	280
Ethanol	190
Methanol	270
CNG	230
LPG	405
Electricity	695
Hydrogen	250

SOURCES AND REFERENCES:

- **Gasoline** — Efficiency rates of 24 MPG for Buick Park Avenue V6; 25 MPG for a Buick LeSabre; 24 MPG for Toyota Camry (G.M.,1992, pp.14, 15, 36); Clean, highly efficient engines already developed in Japan, i.e., M-Miller cycle engine (Japan 21st, 1992); recent impressive gains in mileage, i.e., 65 MPG for a 1992 Honda Civic hatchback VX (Woodruff, 1991, p.56).

- **Ethanol Flex** — Efficiency of 0.0505 ethanol gallons per mile (EPA, April 1990, p.53).

- **Ethanol Neat** — Efficiency of 0.0418 ethanol gallons per mile (EPA, April 1990, p.53).

- **Methanol Flex** — Efficiency of 11.4 MPG for 1992 Ford Econoline Van (NREL, 1992, On line).

- **Methanol Neat** — Dedicated vehicle improvement over gasoline vehicle (CRS, 1989, p.18); dedicated vehicle is 4-15% better in energy input due to higher compression ratios (Oil & Gas, Dec 1991, p.59).

- **Electric** — SAIC data.

- **Electric Hybrid** — SAIC data.

- **CNG** — SAIC data.

- **LPG** — Efficiency for a 1992-1993 Ford F-700 Medium Duty Truck is 15 to 20% less than its gasoline equivalent (N.R.E.L., 1992, On-line).

- **Turbine/Gasoline** — SAIC data.

- **Turbine/CNG** — SAIC data.

- **Fuel Cell/Hydrogen** — Energy density is about 3.8 watts per pound, or less than that of an EV's lead-acid batteries (McCosh, August 1992, p.29); the theoretical limit to energy conversion is 80-85% (Templeman, 1991, p.59).

- **Fuel Cell/Methanol** — See Fuel Cell/Hydrogen above. Both hydrogen and methanol technologies consume hydrogen as a fuel, so they are essentially the same technology, differing only in the way the fuel is stored.

FUTURE EFFICIENCY RATES

Future efficiency rates were obtained by applying an annual percentage gain by technology type, for each of the three penetration scenarios. This section describes how the gain rates were determined and provides the sources used.

ANNUAL PERCENTAGE GAIN IN EFFICIENCY

The following table shows the efficiency gain rates by vehicle technology for three penetration scenarios. Each vehicle technology entry is accompanied by comments or an explanation of assumptions where applicable.

Table F-9. Annual LDV & AFV Efficiency Gain, by Technology (Three Scenarios)

TECHNOLOGY	SCENARIO			EXPLANATION
	BASE	HIGH	LOW	
Gasoline & Diesel	1.00%	0.00%	2.00%	Based on historical rate, i.e., since 1974 GM vehicles have improved efficiency by 125%, and assuming current trends continue, i.e., increased investment in order to meet policy goals and competitive challenges of AFV's. The efficiency escalation rate cannot remain constant, because the easier gains have been already achieved. Nevertheless, even the auto-makers themselves have set ambitious goals, i.e., Chrysler's 29 MPG by 1996. Diesel rate parallels gasoline's and is consistent with the historical record.[20]
Alcohol Fuels	1.00%	2.00%	0.50%	5-10% operation efficiency increase through technological improvements in the near future. Since ethanol and methanol have higher heat content than gasoline or diesel, higher efficiency can be expected from a vehicle that runs on neat fuel, but the annual gains in efficiency would be almost the same for both neat and flex fuels.
Electric & Electric Hybrids	0.50%	0.75%	0.00%	Much higher initial efficiency, but fast improvements in battery and/or engine technology are unlikely, resulting in a relatively low efficiency gains rate. Note that this technology is not affected by the Carnot cycle's theoretical limit. Similar rates are projected for all types of hybrids, as their respective complementary technologies are secondary to the electric technology.
CNG & LPG	1.00%	2.00%	0.50%	Gain rates equivalent to those of alcohol fuels assumed.
Turbine/ Gasoline	1.25%	0.00%	2.00%	Based on existing technology applied to other types of vehicles, i.e., Abrahms M1 tank, hovercraft, and assuming the technology will fulfill its theoretical expectations once applied to passenger vehicles. Efficiency gains should parallel those of conventional gasoline vehicles to a large extent.
Turbine/CNG	1.25%	2.00%	0.50%	See TURBINE/GASOLINE entry above. Efficiency gains should parallel those of conventional CNG vehicles to a large extent.
Fuel Cell/ Methanol & Hydrogen	1.25%	2.00%	0.00%	Although the technology is in its infancy, because of its vast potential a fast gain rate similar to that of turbines is expected, i.e., it has a theoretical efficiency of 80 to 85% when the heat of the process is recovered for use elsewhere. It is assumed that there will be continuous technical breakthroughs as projected today, i.e., proton exchange membrane, or other advanced systems fully developed.

SOURCES AND REFERENCES:

- **Gasoline** — Carnot cycle's theoretical maximum (Romano, 1989, p.75); 2-stroke engine (The Economist, September 28, 1991 & Scientific American, October 1992,

[20] Regardless of fuel choice, all ICE's are limited by the Carnot cycle's theoretical maximum of 40 to 50%.

pp. 112-113); super-light materials (GM, 1992, p.14, 15); reduced air drag, upgraded on-board computers (Woodruff, 1991, p.56); reformulation (Unzelman, 1991,p.64). Since 1974 GM vehicles have improved efficiency by 125% (GM, 1992, p.14, 15); Chrysler's efficiency goal is to achieve an average 29 MPG by 1996 (Woodruff, 1991, p.54).

Already existing promising prototypes (Maruyama, 1991); policy and industry goals in the U.S. and elsewhere (Woodruff, 1991, p.54); CAFE's standards by 2001; the historical efficiency escalation rate, defined as a reduction in gallons/year per vehicle, is 4.95% (Oil & Gas, Dec 1991, p.58).

- **Diesel** — Carnot cycle's theoretical maximum (Romano, 1989, p.75); super-light materials (GM, 1992, p.14, 15); reduced air drag, upgraded on-board computers (Woodruff, 1991, p.56); reformulation (Unzelman, 1991,p.64).

- **Ethanol Flex** — 5-10% operational efficiency increase (Oil & Gas, Dec 1991, p.59); Carnot cycle's theoretical maximum (Romano, 1989, p.75).

- **Ethanol Neat** — Higher heat content and efficiency rates; learning curve gains of 20 to 30% over gasoline by the time dedicated vehicles enter the market (CRS, 1989, p.18); Carnot cycle's theoretical maximum (Romano, 1989, p.75).

- **Methanol Flex** — 5-10% operational efficiency increase over gasoline (Oil & Gas, Dec 1991, p.59); Carnot cycle's theoretical maximum (Romano, 1989, p.75); improvement over gasoline: low case 4%, base 6%, and high 13% (CRS, 1989, p.18).

- **Methanol Neat** — Higher heat content and efficiency rate; learning curve gains of 20 to 30% over gasoline by the time dedicated vehicles enter the market (CRS, 1989, p.18); Carnot cycle's theoretical maximum (Romano, 1989, p.75).

- **Electric** — SAIC data.

- **Electric Hybrid/Large I.C.E.** — Efficiency rates of 36 MPG for an average passenger vehicle, and 21 MPG for a light truck (A.F., 1990, p.18-22).

- **Electric Hybrid/Small I.C.E.** — Efficiency rates of 36 MPG for an average

passenger vehicle, and 21 MPG for a light truck (A.F., 1990, p.18-22).

- **Electric Hybrid/Turbine** — (The Economist, September 28, 1991, p.95).
- **CNG** — Carnot cycle's theoretical maximum (Romano, 1989, p.75).
- **LPG** — Carnot cycle's theoretical maximum (Romano, 1989, p.75).
- **Turbine/Gasoline** — (The Economist, September 28, 1991, p.95).
- **Turbine/CNG** — (The Economist, September 28, 1991, p.95).
- **Fuel Cell/Hydrogen** — (Templeman, 1991, pp.59-60).
- **Fuel Cell/Methanol** — (Templeman, 1991, pp.59-60).

VEHICLE EMISSIONS

This section describes vehicle emissions from conventional and ATF vehicles over time.

INDEX APPROACH

The general approach uses an index value tied to the impact-weighted emissions from mid-size gasoline vehicles. In each year from 1990-2030, the emissions impact from the base-case gasoline vehicle is estimated. As gasoline vehicle emissions decline (e.g., due to reformulation), the absolute emissions level declines but the index value remains constant (at 1.0). The emissions impact of the alternative fuels is benchmarked against the absolute level to create the index value for the alternatives. If the emissions of an AFV declines faster than that of the gasoline vehicle, the emissions index for that AFV will decline. If the emissions of an AFV increases or declines less rapidly than that of the gasoline vehicle, the emissions index for that AFV will increase. The technology choice module can make use of this relative indexing in annually selecting vehicle types.

The weight given to emissions and emissions indexing in the technology choice module is outside

the scope of this database. Whether decisions will ultimately be made with respect to some threshold emissions level is also not considered. These two concerns raise certain specification questions discussed elsewhere in this report.

The emissions index is constructed from the following inputs:

- Current emissions from a mid-size car for five pollutants (CO, CO_2, NO_x, methane, and NMHC) in grams/mile for 16 vehicle types. See Table F-10.

- Minimum possible emissions by 2030 for the same pollutants for the same vehicle types. See Table F-11.

- Annual simple percentage decline in emissions towards the minima, same vehicle types.

- Impact-weighting of the five pollutants on health and environmental criteria.

The index constructed from these data is necessary because the impact on human health and the environment from a gram of one pollutant is not equivalent to the impact of another pollutant. This non-equivalence is particularly apparent when one compares the typical emissions of NO_x (about 1 gram/mile) to that of CO_2 (about 450 grams/mile). Clearly, CO_2 is not 450 times more hazardous to health or the environment than NO_x. Thus, a weighting scheme (i.e., an index) must be constructed to properly compare the overall emissions index.

Table F-10. Base Mid-Sized Vehicle Emissions (Grams/Mile, 1990)

TECHNOLOGY	CO	NMHC	MET	NO_x	CO_2	ASSUMPTIONS AND EXPLANATIONS
Gasoline	9.00	1.00	0.00	1.03	452	Representative vehicle for size category. Standard catalytic converter.[21]
Diesel	3.40	0.41	0.00	1.00	450	Representative vehicle for size category. Consistent with data entered under gasoline. Standard catalytic converter.
Ethanol Flex	2.00	0.60	0.00	1.10	435	Consistent with data entered under gasoline and diesel. Retrofitted representative vehicle for size category. Generally higher NO_x than gasoline and diesel due to higher combustion temperature. Formaldehyde not included for methanol emissions.
Ethanol Neat	1.57	0.36	0.00	1.10	429	
Methanol Flex	1.75	0.29	0.00	1.10	447	
Methanol Neat	1.50	0.20	0.00	1.10	450	
Electric	0.00	0.00	0.00	0.00	0.00	Near zero emissions. Rounded off for manageability.
Electric Hybrid/ Large ICE	2.00	0.10	0.00	0.20	90	Due to smaller size and less use, i.c.e.'s emissions are ¼ or less of a conventional engine.
Electric Hybrid/ Small ICE	1.00	0.05	0.00	0.10	45	Due to smaller size and less use, i.c.e's emissions are ½ of large i.c.e.'s
Electric Hybrid/ Gasoline Turbine	0.50	0.03	0.00	0.06	25	Near zero for electric part. See TURBINE entry below. Due to less use and smaller size emission's are about ¼ of conventional turbine's.
CNG	0.30	0.23	1.20	0.97	419	Representative vehicle, consistent with alcohol and gasoline vehicles selected above.
LPG	0.28	0.29	0.00	0.59	437	
Turbine/Gasoline	2.00	0.10	0.00	0.25	100	Theoretically very low emissions, around ¼ of conventional fuel (gasoline or CNG respectively) vehicle.
Turbine/CNG	0.08	0.06	0.35	0.40	95	
Fuel Cell/Methanol	0.00	0.00	0.20	0.01	0.01	Near zero emissions. Small methane figure for methanol vehicle.
Fuel Cell/Hydrogen	0.00	0.00	0.00	0.01	0.01	

[21] For all technologies, pollution produced by the power source or fuel production process is not included.

Table F-11. Minimum Possible Emissions, Mid-Size Vehicle (Grams/Mile, 2030)

TECHNOLOGY	CO	NMHC	MET	NO_x	CO_2	ASSUMPTIONS
Gasoline	1.70	0.04	0.00	0.20	250	Advanced catalytic converters and reformulation.[22]
Diesel	1.25	0.04	0.00	0.20	250	
Alcohol Fuels: Flex & Neat	1.00	0.04	0.00	0.20	250	Advanced catalytic converters.[23]
Electric	0.00	0.00	0.00	0.00	0.00	Power source and accidental leakage not included.
Electric Hybrid/ Large ICE	0.40	0.01	0.00	0.04	60	Due to less use and smaller size, ICE's emissions are ¼ or less of conventional engine.
Electric Hybrid/ Small ICE	0.20	0.01	0.00	0.02	30	Due to smaller size, ICE's emissions are ½ of large ICE hybrid.
Electric Hybrid/ Gasoline Turbine	0.01	0.00	0.00	0.01	12	Advanced catalytic converter and reformulation.
CNG	0.20	0.01	0.20	0.20	250	Advanced catalytic converter.
LPG	0.10	0.04	0.00	0.20	250	
Turbine/Gasoline	0.50	0.02	0.00	0.05	25	Advanced catalytic converter and reformulation.
Turbine/CNG	0.05	0.00	0.05	0.05	25	Advanced catalytic converter.
Fuel Cell/Methanol & Hydrogen	0.00	0.00	0.00	0.01	0.01	Negligible emissions.

[22] For all technologies, emissions from fuel source and accidental leakage is not included.

[23] For ethanol, the 30 to 50% emissions reduction must be weighed against the considerable CO, CO_2 and nitrogen compounds produced by growing, fertilizing, harvesting, drying and transporting the crops to produce the fuel. EPA estimates the pollution created by producing and burning a gallon of ethanol is up to six times as much as producing and burning a gallon of gasoline. However, aldehydes are not produced (Frank, August 1992, p.106).

IMPACT WEIGHTING

The weighting scheme assumes that all impacts will be in the area of health (85% of the decision) or environment (15%) and will be based on each pollutant's contribution to impacts in those areas. For example, CO_2 has an impact on the environment but little or no impact on health. For CO, the reverse is true. Note that we are not considering health impacts derived from environmental impacts as health impacts. We are using the more conventional understanding that, for example, CO_2 is not considered a respiratory hazard (health) but is a greenhouse gas (environment).

In general, the reasoning behind the weightings is as follows:

- **Carbon Monoxide (CO)** — A moderate health hazard for its role in surface-level ozone creation; its environmental effect is negligible.

- **Non-Methane Hydrocarbons (NMHC)** — Serious health hazard for its significant role in surface-level ozone creation; its environmental effect is negligible.

- **Methane (Met)** — Important greenhouse gas; negligible health threat.

- **Nitrogen Oxides (NO_x)** — Serious health hazard for their role in surface-level ozone creation; also a significant greenhouse gas.

- **Carbon Dioxide (CO_2)** — Statistically insignificant health impact but some greenhouse impact.

The choice of the five pollutants (CO, CO_2, NO_x, methane, and NMHC) was based partly on the availability of detailed technical literature and partly on SAIC's judgment about the pollutants likely to affect vehicle choice and public policy in the coming decades. Additional pollutants, notably aldehydes and particulates, could have been added. The ultimate selection of five pollutants was based on computational tractability. The specific inclusion of methane and non-methane hydrocarbons was based on the need to distinguish natural gas-fueled vehicles based on smog-related and non-smog-related emissions. The impact of the various pollutants per unit emitted is assumed not to change over time.

Table F-12. Pollutant Impact Weighting Factors (Health vs. Environment)

IMPACT	WEIGHT	CO	NMHC	MET	NO_x	CO_2
Health	0.85	0.02	0.44	0.00	0.39	0.00
Environment	0.15	0.00	0.00	0.09	0.06	0.0005

The database treats electric vehicles as zero-emissions vehicles (ZEVs) in accordance with California regulations and shows them with zero emissions. Powerplant emissions are not included in the database. Emissions for the gas turbine engines are generally guesses. Emissions levels for the fuel cells are approximately zero, except for NO_x. The emissions for converting coal or natural gas to methanol or hydrogen for use in the fuel cells are not included. Similarly, emissions from ethanol exclude the CO, CO_2, and nitrogen compounds emitted during growing, fertilizing, harvesting, drying, and transporting the crops. Emissions and leakage from tanks (e.g., CNG and hydrogen releases) are also not considered.

DECLINES IN EMISSIONS OVER TIME

The simple annual percentage rate at which the vehicle emissions decline is based on an extensive review of the literature for both the vehicles and the fuels. The decay rates are provided in the following table.

Table F-13. LDV & AFV Emissions Decay Rates

TECHNOLOGY	CO	NMHC	MET	NO_x	CO_2
Gasoline & Diesel	10.0%	10.0%	0.0%	5.0%	0.0%
Alcohol Fuels/Neat & Flex	5.0%	10.0%	0.0%	5.0%	0.0%
Electric Hybrids/ICE & Turbine	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	5.0%	10.0%	10.0%	5.0%	3.0%
LPG	5.0%	10.0%	0.0%	5.0%	3.0%
Turbine/Gasoline	10.0%	10.0%	0.0%	5.0%	0.0%
Turbine/CNG	5.0%	10.0%	10.0%	5.0%	3.0%
Fuel Cell/Methanol & Hydrogen	0.1%	0.1%	0.1%	0.1%	0.1%

In general, the following factors were considered.

- **Gasoline** — Development of upgraded on-board computers for more precise spark timing and fuel injection (so gasoline burns more completely and less HC's escape); widespread use of catalytic converters that will eliminate up to 99% of CO and NO_x pollution by electronically preheating before a car starts; consequent increase in CO2.

- **Electric** — Assigned zero emissions in isolation of power source, therefore decay function is also zero. Even if power source is included there will be dramatic reductions compared to gasoline emissions, depending on fuel burned (natural gas or coal) to generate power. Improvements in emission controls at the source are expected to keep electricity ahead of gasoline.

- **Electric Hybrid/Gas Turbine** — Gas turbine would emit insignificant amounts of pollutants, so they may not need a catalytic converter. Without including power source, the electric part would have zero emissions (see above paragraph.) Although not yet engineered as such, turbine technology has been fully developed.

- **Turbine/CNG** — Widely used in other applications, with well-known emissions. For passenger vehicle applications this technology will emit insignificant amounts of pollutants and may not need catalytic converters.

SOURCES AND REFERENCES:

- **Gasoline** — Clean, highly efficient vehicles such as the M-Miller Cycle engine vehicle are being developed in Japan (Japan 21st, 1992).

- **Methanol Neat** — A dedicated vehicle has higher compression ratios, thus higher heat and NO_x than gasoline I.C.E.; high level of formaldehyde (Oil & Gas, Dec 1991, p.59); high level of carcinogen formaldehyde (Oil & Gas, Dec 1991, p.59).

- **CNG** — The cleanest running nonelectric production vehicle available today full-size Dodge van (Frank, August 1992, p.105). CO level is 1/2 to 1/10 lower, but NO_x is higher due to higher peak combustion temperature in the presence of excess oxygen (Oil & Gas, Dec 1991, p.59).

- **LPG** — Low CO and HC, higher NO (Oil & Gas, Dec 1991, p.60). In the 1992 Ford F-700 Medium Duty Truck, HC and NO_x are significantly lower than their conventional equivalent, while CO emissions are comparable (NREL, 1992, On line).

- **Fuel Cell/Hydrogen and Methanol** — Would meet California's no-emissions requirements for 1994 (McCosh, 1992, p.29); cleanest emissions of any fuel; emissions are water and a low quantity of NO_x (SAIC/report, 1991, p.22); temperature of the electrochemical reaction is low enough to keep NO_x from being a problem (Romano, 1989, p.75).

  Production process reverses gains in emissions; CO2 & NO_x are byproducts of hydrogen production (Ondrey, 1992, p.30).

  Japan in investing in hydrogen-burning vehicles that are far cleaner than any other AFV (Maruyama, 1991); environmentally friendly HR-X by Mazda, a prototype with a hydrogen-burning rotary engine developed already (Japan 21st, 1992).

- **Gasoline** — Upgraded on-board computers for more precise spark timing and fuel injection; future catalytic converters may eliminate 99% of pollution by electronically preheating before a car starts (Woodruff, 1991, p.56).

  Possibilities of catalytic converters: Ford's 1993 Escort/Mercury Tracer models pass California's 1994 TLEV standard; Corning's EHC prototype passes 1997 ULEV standard (Cogan, September 1992, ps.35); 96% HC and 76% NO_x reduction comparing 1992 to 1960's vehicles (Frank, August 1992, p.103); improvements in refueling connection (Oil & Gas, Dec 1991, p.38). By 2003 the CAA could require 25% of all US cars to cut HC by 40%, and NO_x by 50%. By 2006 100% of US cars must meet that standard (Woodruff, 1991, p.59).

- **Electric** — Dramatic reductions compared to gasoline emissions depending on fuel burned (natural gas or coal), emissions controls at the power plant and type of generating equipment (Frank, August 1992, p.105).

- **Electric Hybrid/Turbine** — No direct reference. See relevant entries ELECTRIC above and TURBINE below.

- **CNG** — Considerable improvement potential for emissions in three areas: fuel metering and mixing, lean/dilute combustion systems, catalytic converters (Weaver, 1991, ps.4-7).

- **Turbine/Gasoline** — Gas turbine would emit insignificant amounts of pollutants, may not need a catalytic converter (The Economist, September 28, 1991, p.95).

- **Fuel Cell/Hydrogen** — Hydrogen already is the cleanest fuel available; only emissions are water and small quantities of NO_x (SAIC/report, 1991, p.22).

FUEL OPERATING COST

This section documents fuel operating cost in the database. The output of the database is operating cost for eight fuels, for nine regions, through three penetration scenarios (base, high, and low), from 1990 to 2030. The results are expressed in constant 1990 $/MMBtu.

The general approach is to establish the current national average fuel operating cost for each fuel. Regional differences are obtained using a percentage deviation from the minimum regional price and are assumed to remain constant over time. The sustainability of any such regional price deviations absent government intervention (or unusually skewed tax policies) is questionable. This issue is raised in Section 2 of the report.

Projected operating costs are found using a compound annual percentage fuel price escalation rate for each individual fuel, for each scenario (base, high, low).

The inputs used to forecast fuel costs are:

- Fuel operating cost in 1990 $/MMBtu.
- Regional fuel price differences, as a percentage deviation from the minimum regional prices, by region, by fuel.
- Fuel price escalation, compound annual percentage, all fuels individually, by scenario.

The approach has the following advantages:

- Projected fuel prices should be relatively consistent vis a vis conventional gasoline and other fuel prices.
- Updating and revising figures based on future developments are facilitated.

CURRENT AVERAGE FUEL OPERATING COST

Operating cost is derived from the current national average retail price usually given in $/gallon or similar measure. To allow comparisons between fuels, retail price was converted into dollars per energy content ($/MMBtu). Retail prices by fuel are tabulated below.

Table F-14. Average Fuel Prices, $1990

FUEL TYPE	RETAIL PRICE ($/MMBtu)
Gasoline	$9.70
Diesel	$7.69
Ethanol	$14.55
Methanol	$19.23
CNG	$8.50
LPG	$7.83
Electricity	$23.53
Hydrogen	$30.00

REGIONAL DIFFERENCES, ASSUMPTIONS, AND CRITERIA

Regional fuel prices are calculated by adding a percentage price differential to the national average retail prices found in the preceding table. The price differentials for each region shown in Table F-15 are based on factors such as proximity or access to major ports, production fields, refineries, state/regional consumer price index, adequate infrastructure, local producer and

government support. These factors, assumptions and caveats are discussed after the table. The subsequent notes raise questions about the sustainability of these differences in a national market.

Table F-15. Regional Fuel Price Differences

FUEL TYPE	PERCENTAGE DIFFERENCE BY REGION								
	NE	MA	SA	ENC	ESC	WSC	WNC	MTN	PAC
Gasoline	0.05	0.025	0.025	0.01	0.025	0	0.05	0.025	0.01
Diesel	0.05	0.025	0.025	0.01	0.025	0	0.05	0.025	0.01
Ethanol	0.075	0.0375	0.037	0	0	0.01	0	0.0375	0.05
Methanol	0.05	0.025	0.025	0.01	0.025	0	0.05	0.025	0.01
CNG	0.05	0.025	0.0375	0.025	0.025	0	0.025	0	0.025
LPG	0.05	0.025	0.025	0.01	0.025	0	0.05	0.025	0.01
Electricity	0.1	0.05	0.025	0.01	0.025	0.01	0	0	0.0375
Hydrogen	0.05	0.025	0.025	0.01	0.025	0	0.05	0.025	0.01

Abbreviations:

NE New England
MA Mid Atlantic
SA South Atlantic
ENC East North Central
WSC West South Central
WNC West North Central
MTN Mountain
PAC Pacific

EXPLANATIONS

- **Gasoline** — In the U.S. national market gasoline prices are essentially the same.

- **Diesel** — In the U.S. national market diesel prices are essentially the same.

- **Ethanol** — Mainly produced from corn in Midwest states; the regions that are part of it, or closest to it, enjoy lower prices due to advantages such as access,

convenient transportation, and local support (i.e., state subsidies, farmers interests).

- **Methanol** — Mostly imported, therefore regions enjoying proximity and easy access to major ports and processing infrastructure, i.e., Los Angeles and New Orleans, would have a price advantage. The Pacific region also benefits from California's acute interest in this fuel, i.e., special incentives from the state. Inflexible infrastructure and the high cost of living in NE and WNC explain higher prices in those regions.

- **Electricity** — Regions with access to relatively abundant and cheap power produced by hydroelectric and coal-fired power plants benefit, e.g., WNC, WSC, MTN, and ENC. More expensive power from regions without low-cost fossil fuels drives prices up in NE and MA.

- **CNG** — Proximity to the rich fields in WSC and MTN benefits those regions and ESC, WNC, ENC and PAC. Competing imports benefit areas near major ports, i.e., PAC, ESC. The high cost of living and inaccessibility to fields drive prices up in NE.

- **LPG** — Access to competitive imports and refineries benefits PAC, ESC and ENC. Local production and support would benefit ENC and PAC. Higher transportation costs, infrastructure inflexibility and higher cost of living puts NE at a disadvantage.

- **Hydrogen** — Access to abundant raw materials, i.e., especially low-cost electricity benefits such regions as PAC, ENC, SA, WSC. Infrastructure and local support also push prices down in PAC. WSC, and MTN.

IMPORTANT ASSUMPTIONS AND CAVEATS

- Regional fuel price differences may persist due to transportation costs from producing or importing regions. These differences, however, are likely to be no more than $.05/gallon equivalent and are generally less than differences in state excise taxes.

- Differences in state excise taxes within a region can easily exceed differences in transportation costs from region to region.

- Electricity is shown at an average price. Off-peak electricity will cost less and on-peak electricity will cost much more. If EV sales are induced with the promise of daytime refueling at the office, much higher charges than those shown on the table will apply.

PROJECTED FUEL OPERATING COSTS

Projected fuel operating costs are found using a fuel price escalation rate. This section describes the escalation rate in more detail, and provides a representative sample of the output.

FUEL PRICE ESCALATION RATE

The escalation rate is a compound annual percentage, applied to each fuel individually. The rates for each fuel and the assumptions behind them are shown below.

Table F-16. Fuel Price Escalation Rates

FUEL	RATE	EXPLANATION AND ASSUMPTIONS
Gasoline Diesel	2%	Rate consistent with projections of oil prices based on current and future demand, output, refining capacity, etc.
Ethanol	3%	Mostly from domestic production, ethanol is a net energy loser (which implies the need of subsidies to make it competitive.) Assuming the cost of subsidies is incorporated, and due to the cyclical nature of the corn crops, the escalation rate would be the highest for all ATFs.
Methanol	1%	Assuming it is produced mostly from cheap imports without significant supply disruptions.
Electricity	1%	Assuming most power is used during off-peak hours when power plants have excess capacity. Also assuming regions with excess capacity will compensate for areas where increasing capacity would be prohibitive.
CNG	1%	Mostly from cheap, large fields in the U.S.
LPG	1%	Mostly from domestic production.
Hydrogen	1%	Assuming the current trend in production costs reduction continues, and assuming that sufficient power for production process is obtained from a reliable source.

SOURCES OF ESTIMATES:

- **Gasoline** — Escalation rates for periods: 1990-95 = 1.3%, 1995-2000 = 3.18%, 2000-2005 = 1.63%, 2005-2010 = 1.24 (D.O.E., July 1991, p.25); escalation rates due to reformulation: from 1990 to 2010 a 13.53% increase every five years (SAIC & Oil & Gas, Dec 1991, p.61). Fuel prices will go up as oxygenate-hydrocarbon shift takes place by replacing aromatics with ethers (Unzelman, 1991).

- **Diesel** — SAIC.

- **Ethanol** — Current production is 1 billion gallons per year; 3 to 8 billion gallons possible by 2010 without exerting strong upward pressure on feedstock prices.

- **Methanol** — Increase of 19.31% every ten years (SAIC & Oil & Gas, Dec 1991, p.60).

- **Electricity** — SAIC.

- **CNG** — Increase of 29.18% every ten years (SAIC & Oil & Gas, Dec 1991, p.60).

- **LPG** — Increase of 27.94% every ten years (SAIC & Oil & Gas, Dec 1991, p.60).

- **Hydrogen** — Projected operating costs for five-year intervals: $0.69 per mile by year 2000, down to $0.18 by 2005, $0.15 by 2015, and $0.12 by 2020 (SAIC/report, 1990); the fuel is projected to be cost equivalent with $1/gallon of diesel in the near future (SAIC/Ballard, 1992, p.1-22); demand stimulated by the Clean Air Act (CAA) of 1994; already there is new related investment; new production processes could cut costs by 5-10% and increase capacity by 50% (i.e., high temperature steam electrolizer); 80% of production costs are electricity-related (Ondrey, 1992, pp.31-35).

FUTURE FUEL PRICES IN THE LITERATURE
(In Gasoline-Gallon-Equivalent Unless Specified)

- **Gasoline** — $11.00 per MMBtu (reformulated) By the year 2000 (SAIC /report,

1991, p.26). $1.25-1.39 by the year 2000 (C.E.C., 1989, p.11). $1.58 (D.O.E., July 1991, p.25). $0.20 per gallon rise for reformulated gasoline (Woodruff, 1991, p.56). $0.32 per gallon (1990$) for gasoline reformulation for $2.08 pump price in the year 2010; 26 cents for $1.70 by 2005 (Oil & Gas, Dec 1991, p.59).

- **Ethanol Flex** — $1-1.50 per gallon under expanded fuel ethanol program; produced from corn (EPA, April 1990, p.i).

- **Ethanol Neat** — $17.70 per MMBtu by year 2000 (SAIC /report, p.26).$2.33 by year 2000 (C.E.C., 1989, p.11).

- **Methanol Flex** — $1.01-1.14 established market with guarantees. $1.14-1.35 with few guarantees (O.T.A., 1990, p.76). $1.39 by year 2000 (C.E.C., 1989, p.11). $2.79 (Oil & Gas, Dec 1991, p.60).

- **Methanol Neat** — $0.55-0.83 wholesale per gallons of methanol, by years 2004-2007 (CRS,1989,p.16). $1.35-1.75 by 2007 (A.P.I., August 1989, p.10). $14.50 MMBtu by year 2000 (SAIC /report, 1991, p.26). $1.29-1.37 during a transition phase, with strong market guarantees,$1.61-1.81 with few guarantees. $0.89-1.09 for an established market, with strong guarantees. $1.02-1.27 with few guarantees (O.T.A.,1990, pp.75-6).

- **Electric** — $18.00 MMBtu by year 2000 (SAIC/report, 1991, p.26). $1.31 by year 2000 (C.E.C., 1989, p.11). $5.28 or 15 cents kw/hr if produced with nuclear power (Oil & Gas, Dec 1991, p.61).

- **CNG** — $9.60 MMBtu by year 2000 (SAIC/report, 1991, p.26).$0.84 by year 2000 (C.E.C., 1989, p.11). $2.16 (Oil & Gas, Dec 1991, p.60).

- **LPG** — $0.98 by year 2000 (C.E.C., 1989, p.11). $1.29 (Oil & Gas, Dec 1991, p.60).

- **Fuel Cell/Hydrogen** — $0.18 per mile (SAIC/report, 1990); below $2.00 if substantial improvements can be made in photovoltaic technology (O.T.A.,1990, p.129). $3.50 if nuclear power costs 15 cents kw/hr (Oil & Gas, Dec 1991, p.61). $0.10 per mile year 2030 (SAIC/report, 1990) More efficient solar energy technology (substantially above 30% today) is needed to produce hydrogen by

electrolysis (Tyler, 1990, p.20); research into photochemical and photovoltaic conversion (Gross, 1992, p.74; & Hodgson, 1991, p.58); pre and post-reformers to increase capacity of existing hydrogen plants, boost yields, no major changes in existing basic technology (Ondrey, 1992, pp.31-35). Efficiency improvements in the production of hydrogen can be expect to reach 70 to 90% once improved electrolysis methods are developed (Tyler, 1990, p.20). Promising production methods may bring hydrogen closer to gasoline's production cost, e.g., photobiological and photochemical conversions (though the latter's theoretical maximum efficiency is 32%)(Hodgson, 1991, p.58); hydrogen is the most likely main energy source replacing oil in all applications in the 21st century (Templeman, 1991, pp.60-61).

FUEL AVAILABILITY

This section documents fuel availability in the database. The output is fuel availability as a percent of gasoline availability for eight fuels, for nine regions, from 1990 through 2030, through three penetration scenarios (base, high, low).

The general approach is to determine current and ultimate fuel availability as a percentage of gasoline availability (assumed to be 1). A number of current fuel availability factors were considered in creating a percentage index for each fuel. Projected availability is determined by changes in these factors over time, which are represented by an exponential rate of closure in the current availability gap between gasoline and each of seven alternative fuels. The rate of closure changes for each of three penetration scenarios (base, high, low).

The data reported in this section are uncertain and of questionable usefulness due to the uncertain specification of availability in the model. The values reported in this section must be read in the light of the subsequent extended comments on modeling problems related to fuel availability.

The inputs used to forecast fuel availability are:

- Current regional fuel availability factors, as a percentage of gasoline availability, for all fuels.
- Fuel availability growth factors, represented as an exponential rate of closure in the availability gap.

The approach has the following advantages:

- Projected alternative fuel availability index values should be relatively consistent vis a vis gasoline and other ATF availability indices.
- Updating and revising figures based on future developments are facilitated.

CURRENT FUEL AVAILABILITY

Current alternative fuel availability regional differences are expressed as a percentage of gasoline availability in the base year 1990 as shown in the following table. Important limitations on these values and their usage are subsequently discussed.

Table F-17. Base Year (1990) Fuel Availability, by Region

FUEL TYPE	NE	MA	SA	ENC	ESC	WNC	WSC	MTN	PAC
GASOLINE & DIESEL	1	1	1	1	1	1	1	1	1
ETHANOL	0.01	0.02	0.02	0.1	0.02	0.02	0.02	0.05	0.05
METHANOL	0.01	0.05	0.02	0.02	0.02	0.02	0.01	0.05	0.1
CNG	0.01	0.02	0.02	0.05	0.02	0.02	0.05	0.05	0.05
LPG	0.01	0.02	0.02	0.05	0.02	0.02	0.1	0.05	0.1
ELECTRICITY	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
HYDROGEN	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

FUTURE AVAILABILITY

Changes in infrastructure and other growth factors that are demanded by an economically significant ATF are discussed in this section, along with pertinent assumptions and caveats.

Future availability is determined by changes in the regional availability factors outlined in the previous section. Such changes affect the differences between gasoline and each ATF, so they are represented by an exponential rate of closure of the availability gap between gasoline and each ATF.

GASOLINE INFRASTRUCTURE AND OTHER GROWTH FACTORS

There are roughly a million gasoline stations in the United States at the present time. For any ATF to be accepted by the public a certain threshold of availability must be reached (aside from economic and other considerations). Attaining the threshold level would require government and private investments in infrastructure in the order of tens of billions of dollars in a very short time. It would also exclude the possibility of having more than one or two competitive different fuels at one time. The infrastructure required would vary considerably from fuel to fuel. The implications are explored for each fuel below.

- **Ethanol and methanol** — a large proportion of the existing equipment could be easily adapted as these two fuels have obvious physical similarities to gasoline, i.e., use same pumps and dispensing equipment. However in the case of methanol, its corrosive nature would demand upgrading the system's reservoirs and pipes. There are additional expenses associated with differences in water tolerance and fuel contamination, fire, and explosion hazards.

- **CNG and LPG** — there is a small infrastructure capable of handling vehicle fleets successfully. Both fuels are, and will continue to be, attractive for the vehicle fleet subset, because a central refueling site can service the entire fleet. However, for private passenger cars, adapting a single existing gasoline service station would require a minimum of $250,000 for a compressor. Such a price tag would rule out a wide distribution network for passenger vehicles unless there is some government subsidy.

- **Electricity** — the extensive existing electricity infrastructure should be capable of servicing a large number of vehicles in terms of megawatts of off-peak capacity. On-peak demand would cause massive cost and availability problems. Moreover, since long refueling time would make service station refueling impossible, costly adapters would have to find a place in every user's household.

- **Hydrogen** — although there is an almost limitless supply of raw materials (e.g., water), there is no existing infrastructure for the distribution of hydrogen. Hydrogen's low mass makes it expensive to store since it must be liquified or bound to other substances. For these reasons reaching the necessary threshold level would involve a much higher price tag than for other ATFs.

EXPONENTIAL RATE OF CLOSURE

The growth factors described above were used to determine the exponential rate of closure in the availability gap between gasoline and each ATF, for each penetration scenario. Assumptions and caveats in addition to the ones outlined above are provided after the table.

Table F-18. Availability Gap Closure Rates, By Scenario

FUEL TYPE	PENETRATION SCENARIO		
	BASE	HIGH	LOW
Diesel	99%	99%	99%
Ethanol	10%	20%	2%
Methanol	10%	20%	2%
CNG	10%	20%	2%
LPG	10%	20%	2%
Electricity	10%	40%	2%
Hydrogen	10%	10%	2%

ASSUMPTIONS AND CAVEATS

- Accelerated exponential rates in all penetration cases, especially in the high case, such that a common market would appear in the United States within ten to twenty years. The market arrival time span for each fuel was calculated based on each fuel individually without any other ATF challenger. Such a individual competition approach is inconsistent with the model specifications.

- Regional differences in availability are highly unlikely in any national market, though they can exist initially.

- Even though regional fuel price differences may persist due to transportation costs from producing or importing regions, availability differences cannot, and will not persist if a national market develops.

- It is not clear what constitutes availability for EV's, i.e., whether refueling time

refers to recharging batteries as opposed to switching them. Therefore arbitrary assumptions have been made for this category.

SPECIFIC REFERENCES AND SOURCES

- **Gasoline** — Reformulated gasoline may require $20 to $40 billion in upgraded refineries (Woodruff, 1991, p.56).

- **Methanol** — Cannot be integrated into current distribution system without modifying the system: water tolerance and fuel contamination, materials compatibility in storage and distribution systems, fire and explosion hazards (A.P.I., September 1990, p.27).

- **CNG** — High pressure compressors cost $250,000 each (Woodruff, 1991, p.57).

- **LPG** — There are 10,000 propane refueling stations in the United States (Frank, 1992, p.106).

- **Hydrogen** — Supply of Hydrogen (Frank, August 1992, p.106).

VEHICLE RANGE

This section documents vehicle range in the database. The output of the database is vehicle range in miles for sixteen technologies for three vehicle sizes, through three penetration scenarios (high, low and base) from 1990 through 2030.

The general approach is to establish range (defined as average current miles between refueling) for a small vehicle, through an extensive literature search. The findings are used as base range figures to derive the other two vehicle sizes (e.g., large and medium) using a range credit or penalty. The credit/penalty is expressed as a percentage that lowers the base small vehicle range. Projected range is found by applying an annual simple percentage gain on the base current figures for each technology.

Thus, the inputs used to forecast vehicle range are:

- Miles between refueling for small cars in 1990, for all technologies.
- Range credit or penalty for mid-size and large cars in 1990, all fuels.
- Annual simple percentage gain in range, by vehicle type to 2030.

The results are displayed in miles for all vehicle-fuel types from 1990 to 2030.

CURRENT VEHICLE RANGE

This section describes current vehicle range. For each technology, the base small vehicle range in 1990 is based on the average number of miles between refueling found in the literature. These figures are shown in the following table, which also features the range credit or penalty for vehicle size. The credit is expressed as a percentage ranging from -10% to -15%, for mid and large size vehicles respectively. Sources for these figures are provided at the end of this section.

Table F-19. Current Small Vehicle Range and Size Range Credit

TECHNOLOGY	RANGE IN MILES (SMALL VEHICLE, 1990)	SIZE RANGE CREDIT	
		MID-SIZE	LARGE SIZE
Gasoline	350	-10.00%	-15.00%
Diesel	400	-10.00%	-15.00%
Ethanol Flex	260	-10.00%	-15.00%
Ethanol Neat	235	-10.00%	-15.00%
Methanol Flex	220	-10.00%	-15.00%
Methanol Neat	196	-10.00%	-15.00%
Electric	120	-10.00%	-15.00%
Electric Hyb/Large ICE	250	-10.00%	-15.00%
Electric Hyb/Small ICE	200	-10.00%	-15.00%
Electric Hybrid/Turbine	300	-10.00%	-15.00%
CNG	225	-10.00%	-15.00%
LPG	300	-10.00%	-15.00%
Turbine/CNG & Gasoline	100	-10.00%	-15.00%
Fuel Cell/Methanol & Hydrogen	100	-10.00%	-15.00%

SPECIFIC REFERENCES AND SOURCES: (Range in Miles)

- **Gasoline** — 424 (U.C.E.T.F., 1990, p.40).
- **Diesel** — 488 (U.C.E.T.F., 1990, p.40).
- **Ethanol Flex** — 331 (U.C.E.T.F., 1990, p.40).
- **Methanol Flex** — 350 for 1991 Ford Taurus 4D sedan; 400 for 1992 Ford Econoline van (NREL, 1992, on line); lower range than gasoline's by 40-43%, by 1995 38-41% (D.O.E., August 1990, p.13); 292 (U.C.E.T.F., 1990, p.40).
- **Methanol Neat** — 265 (U.C.E.T.F., 1990, p.40).

- **Electric** — 120 for 1992 GM Impact (G.M. Impact, 1992); 100 for Ford small van (NREL, 1992, on line); Pb-acid battery = 44, NiFe = 90, NaS = 207 (D.O.E.,August 1990, p.13);100 (U.C.E.T.F., 1990, p.40); 340 at 25 mph for Tokyo Electric Power prototype (Gross, 1992, p.74).

- **Electric Hybrid/Large I.C.E.** — 250 for 1993 Ford small Van (NREL, 1992, on line); 40 for electric engine extended range gasoline i.c.e. for the LA301 by International Automotive Design's (The Economist, September 28, 1991, pp.95,96).

- **Electric Hybrid/Small I.C.E.** — 300 for GM's HX3 gasoline prototype; 40 kilowatt generator to recharge its own batteries (Woodruff, 1991, p.59).

- **CNG** — 200 for 1992 GMC medium-duty truck (GM Natural Gas Powered, 1992); 200 for 1992 Chrysler Dodge B-series van/wagon NREL, 1992, on line); 1990-95 lower than gasoline by 61% (D.O.E.,August 1990, p.13); 106 (U.C.E.T.F., 1990, p.40).

- **LPG** — 34 (U.C.E.T.F., 1990, p.40).

- **Fuel Cell/Hydrogen** — 300-500 with electric engine and improved storage, i.e. liquid or absorption process (Rouse, 1991, p.15); 190 for BMW's liquid-hydrogen storage vehicle; 75 for Mercedes hydracide vehicle (Romano, 1989, pp.60, 61).

PROJECTED VEHICLE RANGE

Projected vehicle range for all technologies is found by applying an annual simple percentage gain to the current base for each technology. The annual gain is assumed to be 1% because most improvements in technology apply equally to all fuels, i.e., reduce air drag, advanced body materials. It is also assumed that there will be similar advances in areas that are not shared because the rationale for investment in R & D is the same regardless of fuel technology, i.e., fuel reformulation, engine enhancements. Market penetration does not affect the annual gain; therefore, the rate of 1% is valid for all penetration scenarios.

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Attachment 3: LDV Stock Module

Fuel Economy Gap Estimation

INTRODUCTION

This attachment presents long-term projections of the fuel efficiency degradation factor for automobiles and light-duty trucks. The projections are based on the analysis of important trends in driving patterns that affect fuel economy. These trends include the increase in urban share driving, urban congestion, and highway speeds. The projections are developed for the period 1990 through 2030. This appendix also outlines other efforts to project fuel economy degradation factors.[24]

BACKGROUND

A discrepancy exists between automotive fuel economy as measured by the Environmental Protection Agency (EPA) under controlled laboratory conditions and the actual fuel efficiency observed under real "on road" conditions. Public and private organizations such as the Department of Energy (DOE), the Environmental Protection Agency (EPA), Ford Motor Company, General Motors Corporation, and Mitsubitshi Motors Corporation have conducted independent research on fuel economy, in the past, confirming this discrepancy.[25] The fuel efficiency degradation factor (also known as "the gap") measures this discrepancy and is defined as the difference between on-road fuel economy and EPA tested fuel economy.[26] When fuel economy is expressed in terms of miles per gallons (MPG), the degradation factor or gap is

[24] This appendix is taken from a report which was prepared by Decision Analysis Corporation of Virginia (DAC) for the Energy Demand Analysis Branch of the Energy Information Administration (EIA), under Task No. 92010, Subtask 1, Contract No. DE-AC01-92EI21946.

[25] Davis, S. and Morris, M., Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 12, ORNL-6710, (Edition 12 of ORNL-5198), p.3-9,March 1992.

[26] Westbrook, F. and Patterson, P., "Changing Driving Patterns and Their Effect on Fuel Economy," presented May 2, 1989 at the 1989 SAE Government/Industry Meeting, Washington, D.C.

formulated as:

$$GAP = \frac{\text{EPA Test MPG} - \text{On-Road MPG}}{\text{EPA Test MPG}} \quad (2)$$

On-road fuel efficiency depends on several determinants which can be classified into technological factors, driver behavior and habits, driving trends, and road and climate conditions. Furthermore, the magnitude of the gap between tested fuel efficiency and on-road fuel efficiency depends on the specific procedures and conditions used during the test and the closeness of the formulations used to represent real driving conditions.

EPA fuel economy estimates for city and highway driving are published every year for each new model available in the U.S.[27] These MPG estimates are obtained based on vehicle tests performed under controlled laboratory conditions and then adjusted downwards to reflect actual driving conditions. Separate tests are used to generate the city and highway MPG estimates.

The EPA city fuel economy estimates are based on a test that simulates a 7.5 mile, stop-and-go trip with an average speed of 20 mph. The trip lasts 23 minutes and has 18 stops. About 18 percent of the time is spent idling, such as waiting for traffic lights or in rush hour traffic. Two types of engine starts are used: a cold start and a hot start. The cold start is similar to starting the car in the morning after it has been parked all night. The hot start is similar to restarting a vehicle after it has been warmed up, driven and stopped for a short time.

The EPA highway fuel economy estimates represent a mixture of "non-city" driving. Segments corresponding to different kinds of rural roads and interstate highways are included. The test simulates a 10-mile trip and averages 48 mph. The test is run from hot start and has little idling time and no stops.

EPA adjusts these laboratory fuel economy estimates downwards to reflect actual driving on the road conditions. In the 1992 Gas Mileage Guide: EPA Fuel Economy Estimates the city estimates are lowered by 10 percent and the highway estimates by 22 percent from the laboratory test results. These adjustment factors represent the EPA estimates of the fuel efficiency gap for both city and highway driving.

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[27] DOE/EPA, Gas Mileage Guide: EPA Fuel Economy Estimates, DOE/CE-0019/10.

Fuel economy can also be represented by a composite number that combines city and highway fuel economies. EPA computes composite fuel economies using the following formulation:

$$\text{EPA Composite MPG} = \left[\frac{0.55}{MPG_c} + \frac{0.45}{MPG_h} \right]^{-1} \quad (3)$$

where:

MPG_c = Miles per gallon for city driving
MPG_h = Miles per gallon for highway driving

EPA's composite formulation is developed based on 55% city driving and 45% highway driving. This formulation, combined with the EPA city and highway fuel efficiency gaps, leads to a base composite MPG gap for all new vehicles of 15 percent.

Previous attempts at estimating the base fuel efficiency gap have been made. In 1978, McNutt et al., measured the gap for model year 1974 through model year 1977 cars. The resulting estimates of the gap were between 6 and 9 percent.[28] In 1984, Hellman and Murrel estimated a composite MPG gap of 15 percent.[29] More recently in 1992, Oak Ridge National Laboratory (ORNL) reported composite gap estimates that apply to all automobiles and light trucks in operation.[30] The ORNL base composite gap estimate for all automobiles in operation pre-1974 to 1989 was 15.2 percent. The ORNL gap estimate for light trucks in operation pre-1976 to 1989 was 28.3 percent. For this analysis, ORNL used EPA tested fuel economy data which was verified by the National Highway Safety Administration (NHTSA). These data were compared against on-road fuel economy data from (1) the Federal Highway Administration (FHWA) Highway Statistics 1989, (2) the Department of Energy, Energy Information Administration, 1988 Residential Transportation Energy Consumption Survey (RTECS), and (3) the Bureau of the Census, 1987 Census of Transportation, Truck Inventory and Use Survey (TIUS).

Very few attempts to forecast trends in the fuel economy gap are available. In 1989, Westbrook and Patterson analyzed trends in driving patterns and produced forecasts of the fuel economy gap

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[28] SAE 780037

[29] SAE 840496

[30] Davis, S. and Morris, M., Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 12, ORNL-6710, (Edition 12 of ORNL-5198), p.3-9,March 1992.

Maples, John D., and Philip D. Patterson, "The Fuel Economy Gap for All Automobiles and Light Trucks in Operation," Draft, Washington, DC,1991.

for the year 2010.[31] Their results indicated a composite gap of 29.7 percent for automobiles for the year 2010. This combined fuel efficient gap corresponded to a city fuel efficiency gap of 23.5 percent and a highway fuel efficiency gap of 30.5 percent. Organizations such as Data Resources Incorporated (DRI) and Wharton Econometrics Forecasting Associates (WEFA) use values for the degradation factors that remain constant over their forecasting horizon. The Department of Energy (DOE) and the Energy Information Administration (EIA) in the 1990 National Energy Strategy (NES) projected the fuel efficiency gap to reach 30 percent by 2030 in the NES reference case.[32] The projected gap for the High Conservation and the Very High Conservation cases of NES were 25 and 20 percent respectively. Also, EIA in the Annual Energy Outlook 1992 (AEO) projected the fuel efficiency gap to increase from 20 percent in 1990 to 25 percent in 2010.

An ongoing effort by DOE's Office of Transportation Technologies in conjunction with the University of Tennessee is focused on forecasting the fuel efficiency gap for automobiles and light duty trucks through 2010. This work considers three scenarios based on differing assumptions about urban shares, highway speed, and congestion trends.

This attachment presents independent projections of the fuel efficiency gap to the year 2030 for two vehicle types:

1) Automobiles, and
2) Light Duty Trucks

The projections are generated based on the analysis of three important trends in driving patterns that affect fuel efficiency. These factors are:

1) increasing urban share of vehicle miles traveled,
2) increasing average highway speed, and
3) increasing level of urban highway congestion.

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[31] Westbrook, F. and Patterson, P., "Changing Driving Patterns and Their Effect on Fuel Economy," presented May 2, 1989 at the 1989 SAE Government/Industry Meeting, Washington, D.C.

[32] EIA, Energy Consumption and Conservation Potential: Supporting Analysis for the National Energy Strategy, SR/NES/90-02, Service Report, p. 89, Washington, D.C., December 1990.

Initially, forecasts for each of these factors were developed based on two different growth scenarios:

1) Logistic Growth, and
2) Linear Growth

These scenarios are fully described as follows, using urban share growth as an example:

Logistic Approach

Figure F-1 shows the historical urban share of automobile VMT driving from 1972 through 1990 and a logistic curve fitted to the historical period and extended through the year 2030. The logistic share values are developed based on a logistic functional form originally formulated by Fisher and Pry [33] and defined by:

$$f_t^U = \frac{f_\infty^U}{1 + e^{-(\alpha + \beta t)}} \tag{4}$$

where:

f_t^U is the urban share in year t,

f_∞^U is the urban share asymptotic limit, α and β are parameters of the logistic curve defined by:

$$\alpha = \ln[f_0^U / (f_\infty^U - f_0^U)], \tag{5}$$

$$\beta = (1/h^U)\ln[(f_\infty^U - f_0^U) / f_0^U], \tag{6}$$

where:

f_0^U is the base year urban share, and

h^U is the halving factor for the logistic curve. The halving factor is the time required from the base year for the urban share to reach the midpoint between its base year value and its asymptotic limit.

[33] Fisher, J.G. and Pry, R.M., "A Simple Substitution Model of Technology Change." Technological Forecasting and Social Change, Vol.3, pp.75-88, 1971.

The logistic curve in Figure F-1 represents the curve that best fits the historical data on urban share for the 1972-1990 period. This curve is generated by assuming two logistic parameters and by selecting a base share year. These two parameters are the asymptotic limit and the halving factor. The asymptotic limit represents an upper limit to the growth of the urban share. The halving factor is a measurement of the time needed for the share to reach this upper limit. The values for both parameters are specific to the best fit curve and they are determined using an iterative approach which minimizes the sum of the squares of the difference between the historical shares and the logistic estimated shares.

Linear Approach

If it is assumed that the urban share will continue growing linearly, the impact on the fuel efficiency gap differs. Figure F-2 shows the historical urban share of automobile VMT driving from 1972 through 1990 and both a logistic curve and a straight line, fitted to the historical period and extended through the year 2030. The linear share forecasts developed by simple regression are considerably larger than those resulting from the logistic functional form.

The conclusions of the report noted that the logistic approach seemed to yield a more realistic projection of the gap. This was based largely on intuition, as the logistic approach can account for constraints which the linear approach cannot. As a result, logistic data were used in forming the model and are presented herein.

A total of two sets of projections were generated for each of the vehicle types, factors, and scenarios. The first was based on the assumption that all urban driving is city driving and all rural driving is highway driving. Fuel economy gap projections generated in the past are based on such an assumption, as it makes the gap calculations considerably easier. However, the assumption oversimplifies reality since some of the urban driving is on interstate highways and other freeways located in urban areas, and some of the rural driving includes stop-and-go city type of driving. The second set of projections were generated taking into consideration the decomposition of urban and rural driving into city and highway driving according to road types. This adjusted city/highway driving share approach was deemed more realistic. This is due to the fact that such an approach more closely resembles actual driving behaviour and consequently avoids the restricting assumption that urban driving is equal to city driving and rural driving is equal to highway driving. As such, only these calculations are included in this appendix.

The decomposition is based on road types. Thus, VMT driving on roads identified as "interstate"

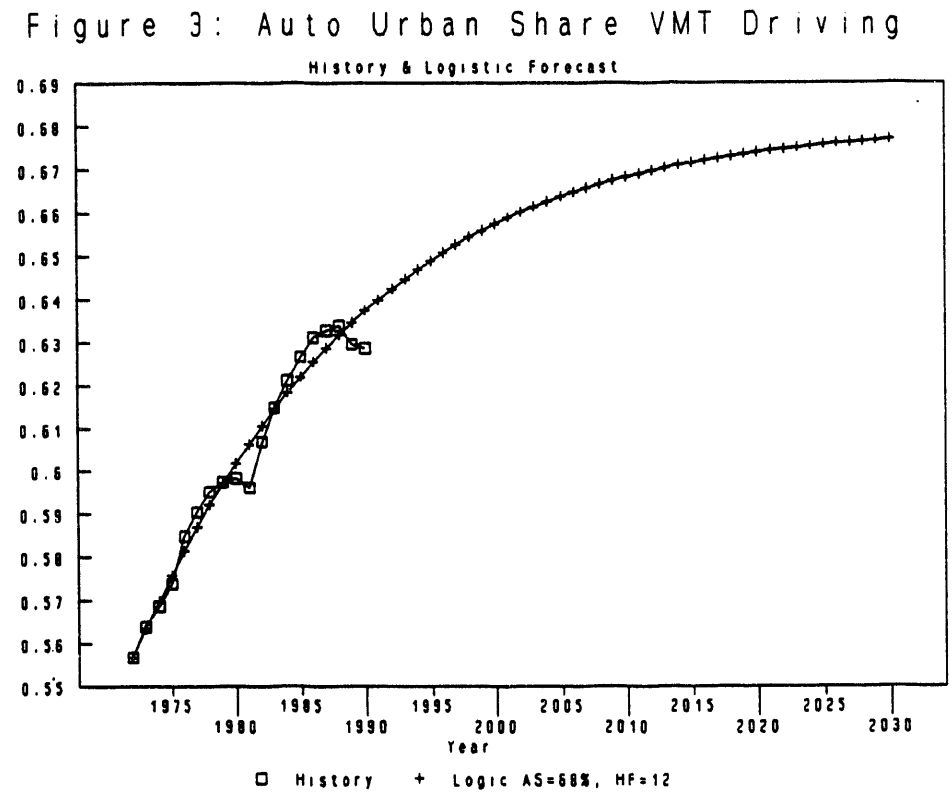
and "other freeways and expressways" in urban areas are considered part of the highway driving share. Other road types located in urban areas are considered part of the city driving share. In addition, VMT driving on roads defined as "minor collectors" and "local" in rural areas are classified as city driving while the rest of the road types in rural area are considered highway driving. Although this road classification does not exactly replicate reality, it is a closer representation of the actual city/highway driving composition.

Approximately 63 percent of total 1990 VMT consisted of driving in urban areas and 37 percent in rural areas. 68 percent of the urban VMT is considered city driving and 32 percent highway driving. In rural areas, 17 percent is considered city driving and 83 percent highway driving. This composition represents overall city and highway driving shares for 1990 of:

City Share:	49.1 %
Highway Share:	50.9 %

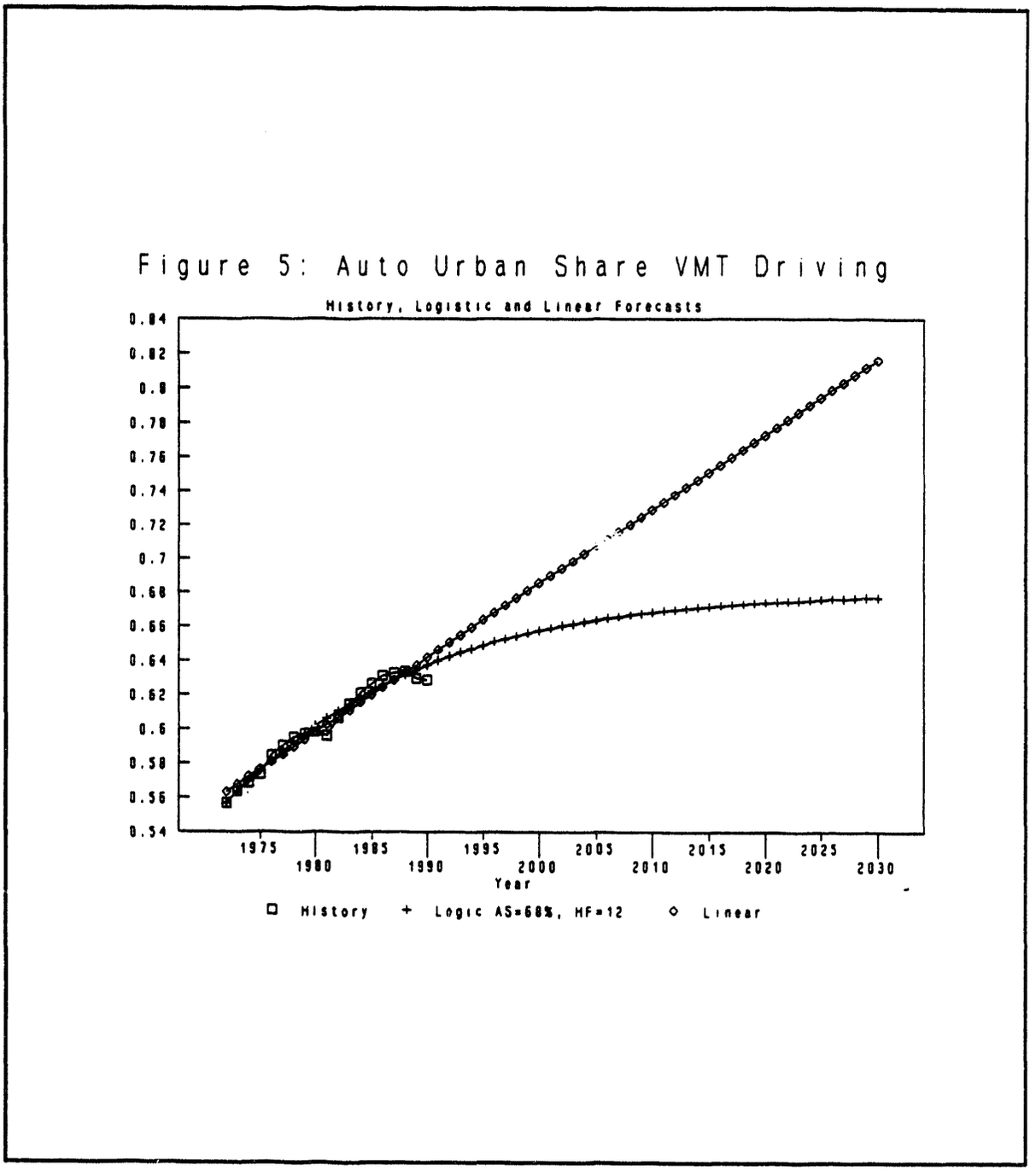
These adjusted city and highway shares are the bases for the calculations of the fuel efficiency gap projections in this chapter. The impact on fuel efficiency, from each of the three factors considered in this study, is affected by these adjusted shares. The impact from the increasing urban share trend is diminished since only part of the urban share (68% in 1990) is considered city share. The impact from increasing highway speeds is amplified since highway driving in both urban and rural areas is considered. Finally, the impact from increasing urban highway congestion is diminished since only part of the urban share is considered highway driving. The resulting fuel efficiency gap projections for automobiles and light duty trucks using the logistic approach based on these adjusted shares will be presented.

Figure F-1. Urban Share of Automobile VMT: Logistic Forecast



Source: Historical Values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

Figure F-2. Urban Share of Automobile VMT: Logistic and Linear Forecasts



Source: Historical Values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

FUEL EFFICIENCY GAP PROJECTIONS

This section outlines the three trends which are assumed to affect the fuel efficiency gap estimates of the EPA. It then presents the projections of the fuel efficiency gap which have been utilized in the NEMS Transportation Sector Model.

Increasing Urban Share Driving

A review of the data from the last few decades on VMT for both automobiles and light duty trucks reflects a continuous increase in the share of urban driving.[34] For automobiles the urban share increased from 45.4 percent in 1953 to 62.9 in 1990. Figure F-3 shows the historical urban share of VMT for automobiles. This represents a 38.5 percent increase in 37 years, or an average annual rate of increase of 0.88 percent. For light duty trucks the urban share increased from 39.5 percent in 1966 to 55.4 in 1990. Figure F-4 shows the historical urban share of VMT for light duty trucks. This represents a 40.3 percent increase in 24 years, or an average annual rate of increase of 1.42 percent.

Westbrook and Patterson investigated the reasons for this increase in urban share by analyzing the data for the period from 1975 through 1985.[35] Their results indicated that the major reasons for this increase are the larger fraction of travel in urban roads and a larger fraction of roads being classified as urban. Population shifts to urban areas and driving shifts within metropolitan areas account for the larger fraction in urban driving which was estimated to be the cause for 58 percent of the increase in urban share. The other 42 percent increase was determined to be the consequence of the reclassification of roads from rural to urban. Any area reclassified by the U.S. Bureau of the Census from rural to urban results in the reclassification of all roads (regardless of the type) as urban.

Forecasts of the shares of urban and highway driving are necessary in order to forecast the change in the fuel efficiency gap due to changes in driving shares. It is very difficult to draw conclusions about the increasing trend in urban driving. Nevertheless, it can be expected that population shifts to urban areas will continue and that future land developments will force

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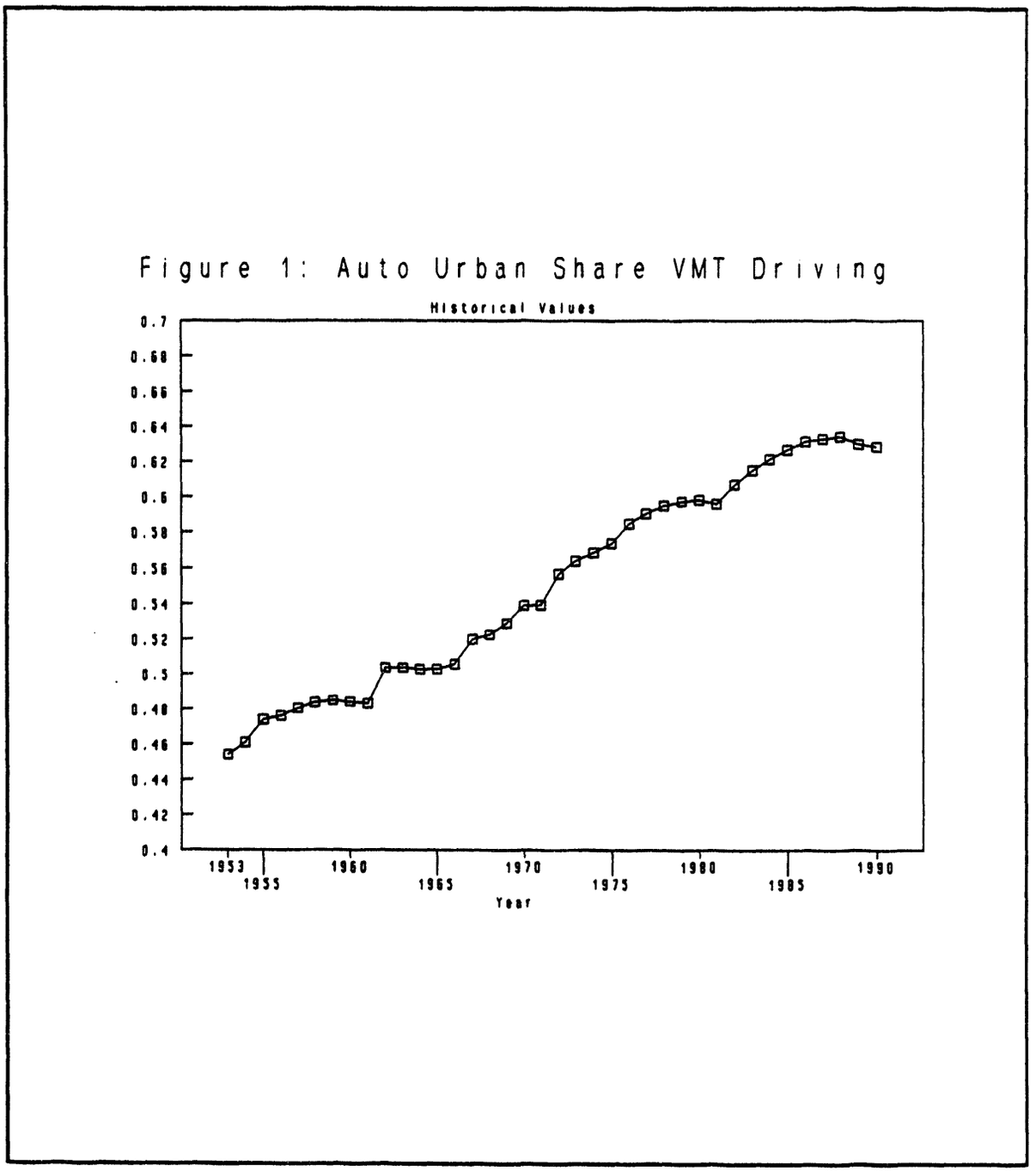
[34] Data on VMT is published annually by the U.S. Department of Transportation, Federal Highway Administration, in Highway Statistics.

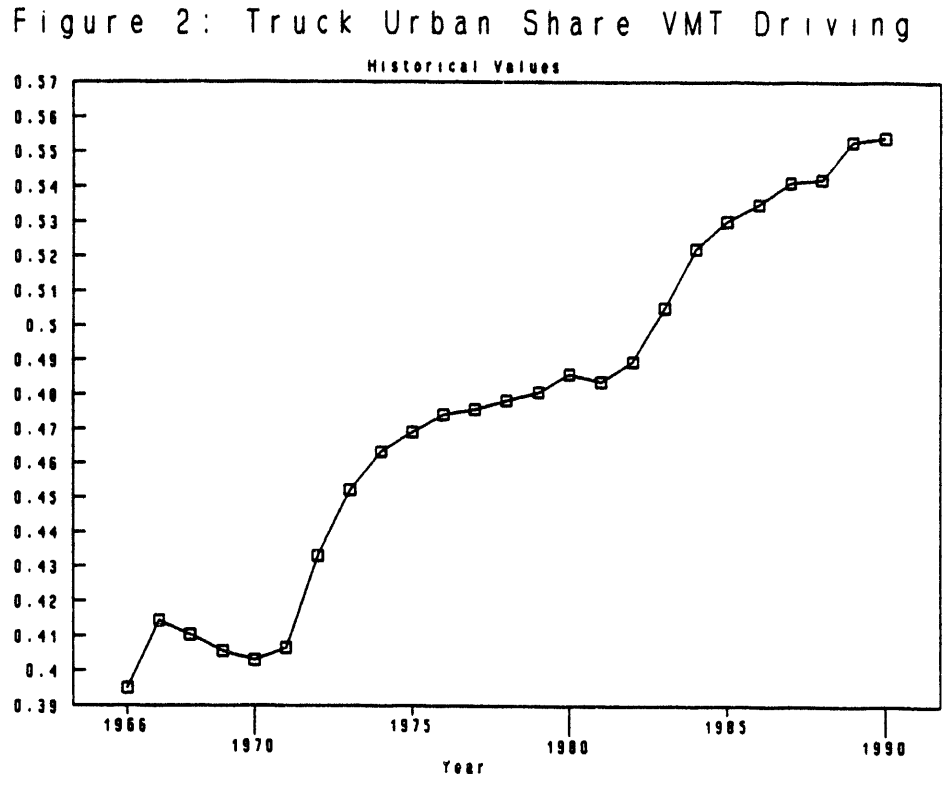
[35] Westbrook, F. and Patterson, P., "Changing Driving Patterns and Their Effect on Fuel Economy," presented May 2, 1989 at the 1989 SAE Government/Industry Meeting, Washington, D.C.

Figure F-3. Urban Share of Automobile VMT: 1953-1990



Source: Historical Values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

Figure F-4. Urban Share of Light Truck VMT: 1966-1990



Source: Historical Values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

the reclassification of rural areas into urban areas. If we assume that this rate of increase in urban share will gradually diminish and level off, the logistic path applies (see Figure F-1). The calculations for logistic growth of increased urban share for automobiles and light trucks follow.

Automobiles:

Table F-20 summarizes the impact of the adjusted logistic city share growth on the composite fuel efficiency gap for automobiles. The adjusted logistic city share projection for the year 2010 becomes 51.1 percent as compared to the unadjusted logistic share of 66.8 percent; in the year 2030, the projection levels off at 51.5 percent as compared to an unadjusted 67.7 percent projected logistically. The adjusted logistic forecasts of city share increase are translated into a fuel efficiency gap of 16.05 percent by the year 2030. This represents an increase of only 0.85 percentage points over the base gap of 15.2 percent.

Light Duty Trucks:

The influence of the adjusted logistic urban share growth on the composite fuel efficiency gap for light duty trucks is presented in Table F-21. For the year 2010 the adjusted logistic city share projection becomes 48.8 percent as compared to an unadjusted logistic share of 62.3 percent. For the year 2030, the projection begins to level off at 50.3 percent as compared to an unadjusted 65.2 percent projected logistically. The adjusted logistic forecasts of urban share increase are translated into a fuel efficiency gap of 29.73 percent by the year 2030. This represents an increase of only 1.43 percentage points over the base gap of 28.3 percent.

Table F-20. Automobile Fuel Efficiency Gap Projections: Logistic Growth of City Driving Share (with Adjusted City Driving Share)

	1988	1990	1995	2000	2005	2010	2015	2020	2025	2030
City Share	49.3%	49.1%	50.1%	50.5%	50.8%	51.1%	51.2%	51.4%	51.5%	51.5%
Base Gap	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20
Gap Forecast	15.27	15.19	15.56	15.73	15.82	15.90	15.97	16.02	16.04	16.05
Change	0.07	-0.01	0.36	0.53	0.62	0.70	0.77	0.82	0.84	0.85

Sources: Base Gap from ORNL 1992, Urban Share Forecasts based on Fisher & Pry Logistic Function.

Table F-21. Light Truck Fuel Efficiency Gap Projections: Logistic Growth of City Driving Share (with Adjusted City Driving Share)

	1988	1990	1995	2000	2005	2010	2015	2020	2025	2030
City Share	44.6%	45.3%	46.3%	47.3%	48.1%	48.8%	49.3%	49.7%	50.0%	50.3%
Base Gap	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30
Gap Forecast	28.30	28.48	28.72	28.98	29.21	29.35	29.50	29.60	29.66	29.73
Change	0.00	0.18	0.42	0.68	0.91	1.05	1.20	1.30	1.36	1.43

Sources: Base Gap from ORNL 1992, Urban Share Forecasts based on Fisher & Pry Logistic Function.

Increasing Highway Speeds

The level of speed of a vehicle is one of the relevant factors that affects its fuel efficiency. Specifically, it has been determined that speeds over 45 mph decrease fuel efficiency for most vehicles. Furthermore, EPA estimates that traveling at 65 mph as compared to 55 mph lowers fuel economy over 15 percent.[36] ORNL's 1992 Transportation Energy Data Book presents the findings of a fuel economy study performed by the Federal Highway Administration in 1984.[37] This study concluded that, on average, vehicles experience fuel efficiency losses of about 17.8 percent when their speed is increased from 55 mph to 65 mph. This is equivalent to a reduction of 1.78 percent for each mile per hour increase over speed ranging from 55 mph to 65 mph.

Average highway speeds in the United States have shown an increasing trend for several years with few exceptions. Figure F-5 presents average highway speeds in mph for the last 45 years. The data in this figure indicate two different increasing trend periods. The first period from 1945 through 1973 corresponds to the largest rate of increase on highway speeds. During these years, highway speed increased at an annual rate of 1.13 percent. In 1973, average highway speed suddenly dropped from about 66 mph to about 55 mph. This sudden drop corresponds to the implementation of the nationwide 55 mph speed limit. After 1974, the increasing trend has continued at a more moderate rate. In the 1974-1990 period the annual rate of speed increase has been 0.15 percent. A closer look at the post-1973 period indicates that through the rest of the 1970s, the average speed remained fairly constant between 55 and 56 mph; and, through the 1980s, the annual rate of increase was 0.34 percent.

The increase in highway speed can also be illustrated by considering the percentage of rural and urban VMT driving over 55 mph on highways with posted speed limits of 55 mph. Figure F-6 presents these data for the 1981-1990 period. In only 9 years, the percent of rural VMT driving over the 55 mph speed limit rose from 46.4 percent to 58.7 percent for a total of 12.3 percentage points. The percentage increase in urban VMT driving was even more dramatic, from 37.6 percent to 53.8 percent for a total of 16.2 percentage points. The percentage exceeding the speed limit is far from homogeneous. Significant differences exist across states, highway types, and location for rural or urban areas. For instance, in 1990 the percentage of vehicles exceeding the 55 mph limit in urban interstate highways in New York was 82.5 as compared to 68.2 in

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[36] DOE/EPA, 1992 Gas Milage: EPA Fuel Economy Estimates, DOE/CE-019/10, October 1991.

[37] Davis, S. and Morris, M., Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 12, ORNL-6710, (Edition 12 of ORNL-5198), Table 3.42, p.3-66,March 1992. 1984 data from U.S. Department of Transportation, Federal Highway Administration, Fuel Consumption and Emission Values for Traffic Models, Washington, D.C., May 1985.

California and only 33.7 in South Dakota.

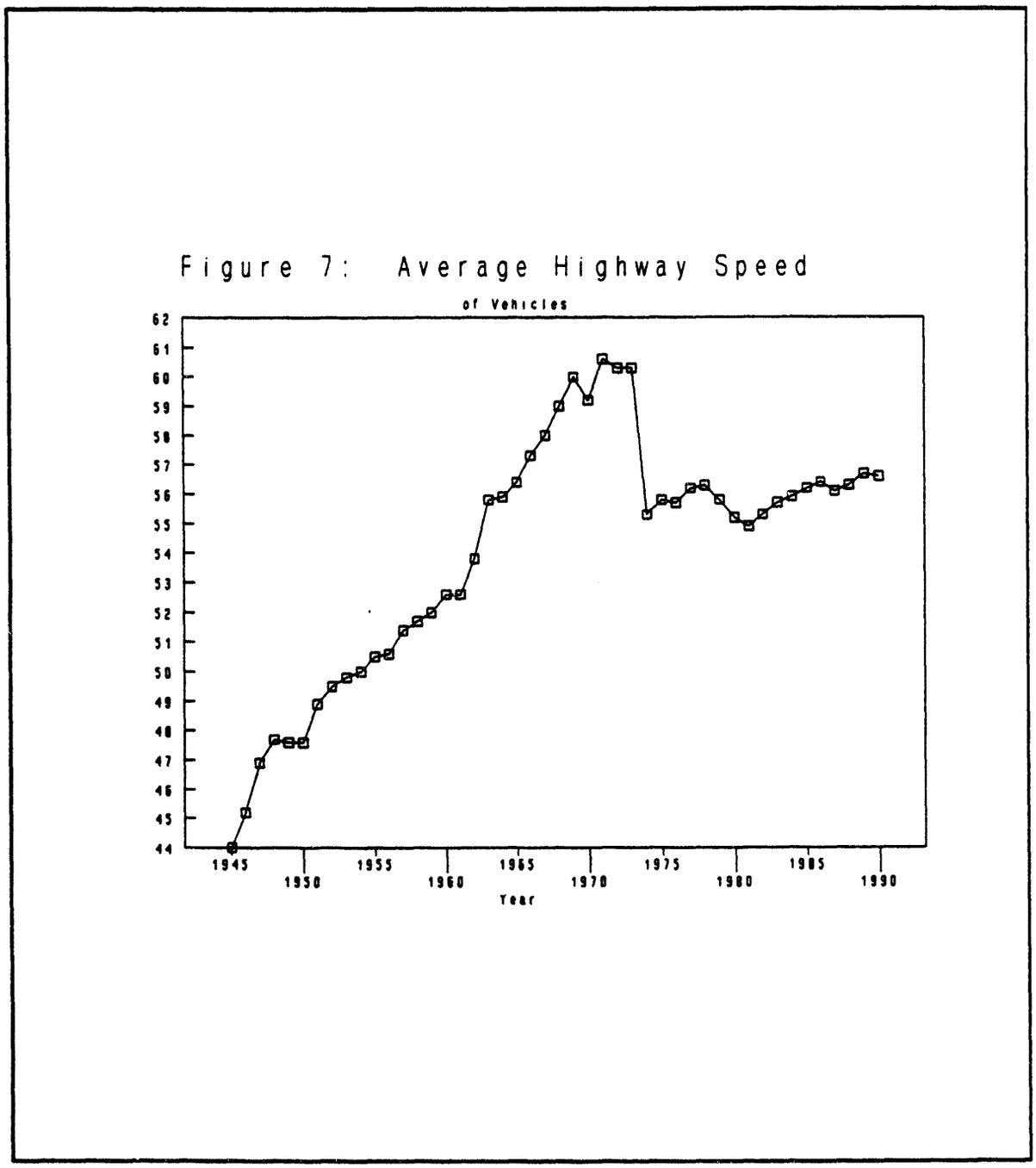
The estimation of the overall impact of speed trends in fuel economy is dependent on the specific data type selected to measure this trend and on the methodology used to forecast this trend. One could choose a disaggregated approach in which speed trend forecasts are developed by urban and rural driving, highway type, and vehicle type, for each state. Given the time limitations, the current study utilizes the nationwide average highway speed for all vehicles and highway types. Average speeds post-1980 are used as the basis to generate forecasts.

As Figure F-5 illustrates, average highway speed is influenced by regulatory policies such as the implementation of the nationwide speed limit in 1973-1974. Other factors affecting speed might include safety and environmental regulations, gasoline prices, oil shortages, income fluctuations, etc. Although a methodology to forecast speed trends which includes all relevant factors is desirable, a logistic approach based on historical trends has been applied.

Automobiles:

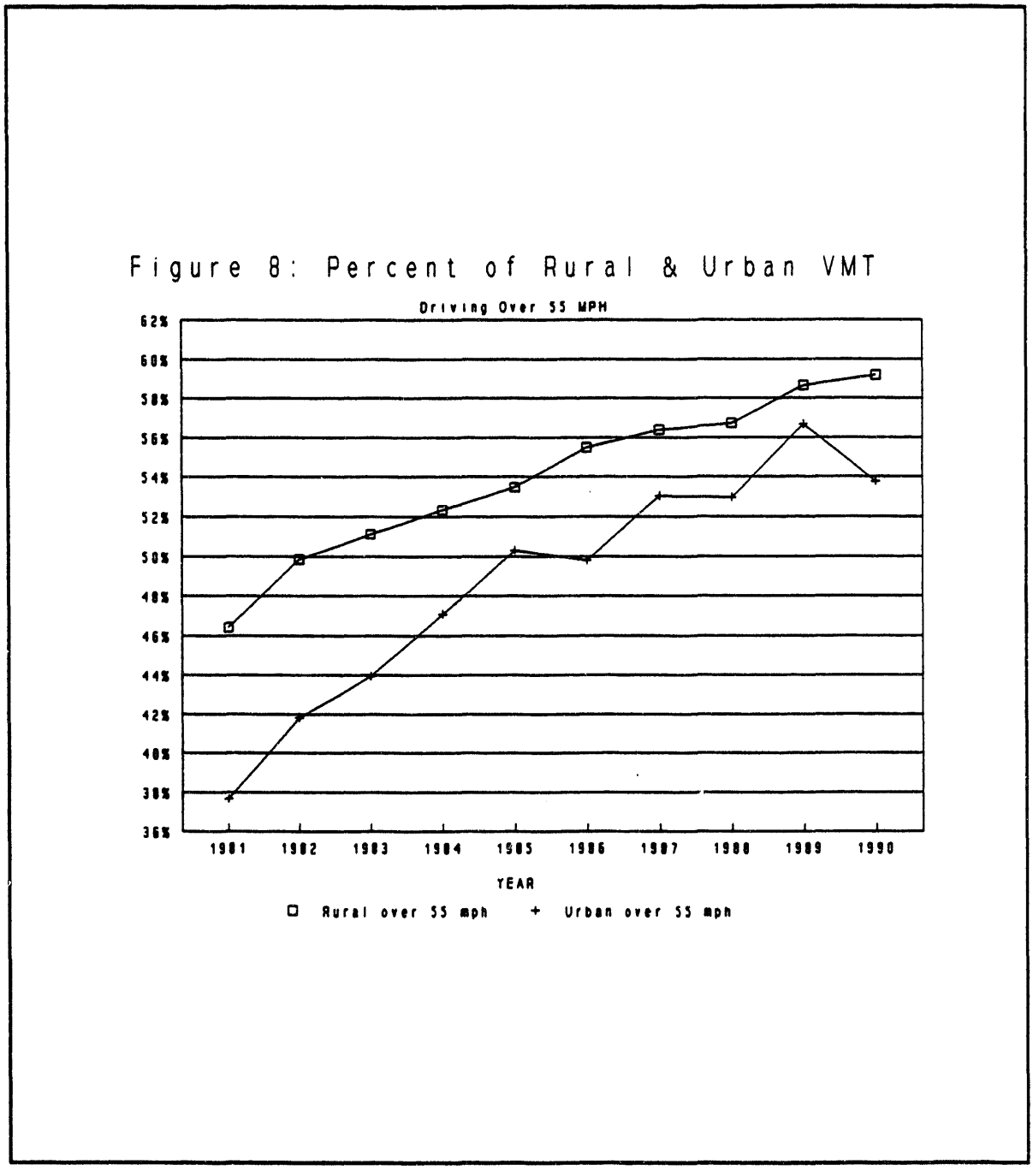
Table F-22 summarizes the impact of the adjusted highway share speeds on the composite fuel efficiency gap for automobiles using the logistic approach. Unlike the adjusted results for the urban driving share, the fuel efficiency gap forecasts indicate that in 2010 the gap has increased to 17.02 percent, which is greater than the unadjusted logistic forecast of 16.58 percent. By the year 2030, the adjusted f[illegible]s 18.27 percent, which is above the unadjusted logistic forecast of 17.47. By the year 2[illegible] adjusted gap is 3.07 percent above the base gap of 15.2 percent.

Figure F-5. Average Vehicle Highway Speed: 1945-1990



Source: Historical Values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

Figure F-6. Percent of Highway VMT over 55 MPH: 1981-1990



Note: Based on data for roads with posted speed limit of 55 mph.

Source: Historical values from U.S. DoT, FHWA, Highway Statistics, different yearly issues.

Table F-22. Automobile Fuel Efficiency Gap Projections: Logistic Growth of Average Highway Speed (with Adjusted Highway Driving Shares)

	1988	1990	1995	2000	2005	2010	2015	2020	2025	2030
Highway Speed,mph	56.30	56.60	57.41	58.06	58.66	59.22	59.75	60.23	60.69	61.11
Base Gap	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20
Gap Forecast	15.19	15.39	15.89	16.31	16.67	17.02	17.38	17.70	18.00	18.27
Change	-0.01	0.19	0.69	1.11	1.47	1.82	2.18	2.50	2.80	3.07

Sources: Base Gap from ORNL 1992, Highway Speed Forecasts based on Fisher & Pry Logistic Function.

Table F-23. Light Truck Fuel Efficiency Gap Projection: Logistic Growth of Average Highway Speed (with Adjusted Highway Driving Share)

	1988	1990	1995	2000	2005	2010	2015	2020	2025	2030
Highway Speed,mph	56.30	56.60	57.41	58.06	58.66	59.22	59.75	60.23	60.69	61.11
Base Gap	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30
Gap Forecast	28.29	28.49	28.95	29.35	29.74	30.07	30.43	30.73	31.01	31.29
Change	-0.01	0.19	0.65	1.05	1.44	1.77	2.13	2.43	2.71	2.99

Sources: Base Gap from ORNL 1992, Highway Speed Forecasts based on Fisher & Pry Logistic Function.

Light Duty Trucks:

Table F-23 displays the fuel efficiency gap projections for light duty trucks assuming logistic growth for average highway speed and an adjusted driving share to reflect the city to highway driving proportion. The adjusted logistic projections imply that the fuel efficiency gap for light duty trucks will be 30.07 percent for an increase of 1.77 percentage points over the base gap in the year 2010. The gap forecast is larger than the unadjusted logistic projection of 29.74 percent. By 2030 the adjusted logistic forecast is 2.99 percent above the base gap of 28.30 percent, while the unadjusted logistic is 2.39 percent above the base gap. This implies a fuel efficiency gap of 31.29 percent in 2030.

Increasing Urban Highway Congestion

Congestion is a primary issue of the domestic transportation system. Urban congestion has increased in the last decades in most metropolitan areas as expansion and improvement of the transportation system lagged behind the rapid growth of travel demand.

The Federal Highway Administration (FHWA) classifies the two major causes of urban road congestion as recurring congestion and non-recurring congestion. Recurring congestion is that congestion which is the consequence of inadequate road capacity, reduction of through-put lanes, narrowing of lane widths, physical barriers, inadequate traffic light synchronization, and other similar causes. FHWA estimates that recurrent congestion accounts for 40 percent of all urban road congestion. Non-recurring congestion is that congestion resulting from disabled vehicles and accidents. FHWA estimates that disablement account for 55 percent of overall urban congestion, with the remaining 5 percent due to accidents.

One of the most important road types within urban areas in which congestion takes place is urban freeways. In 1990, 32 percent of the total vehicle miles of travel in urban areas corresponded to freeways, while freeways comprised only 5.7 percent of the urban roadway mileage.[38] The increase in urban congestion can be further analyzed by considering the increase in urban VMT as compared to the increase in urban lane miles. Data corresponding to the period 1975-1987 indicate that urban VMT demand growth rate is over 4 times the rate of new urban lane capacity growth. This corresponds to an increase in the average urban through-put (urban VMT per mile) of 38.9 percent.

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[38] U.S. DOT, FHA, Highway Statistics 1990.

Differing methodologies have been developed recently to measure the extent and duration of freeway congestion in urban areas.[39] [40] Hanks and Lomax of the Texas Transportation Institute (TTI) have developed congestion indices for 39 urban areas. Table F-24 lists VMT, VMT per lane-mile, congestion indices, and rankings for each of the urban areas analyzed by TTI. Table F-25 lists, in addition to the congestion indices, estimates of the congestion cost per capita for each of these urban areas. Few attempts to forecast urban congestion and its effect on fuel economy are available. [41]

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[39] Cottrell, P., "Measurement of the Extent and Duration of Freeway Congestion in Urbanized Areas,"ITE 61st Annual Meeting, Milwaukee, Wisconsin, Sept. 1991.

[40] Hanks, J., and Lomax, T., Roadway Congestion in Major Urban Areas: 1982 to 1987, Texas Transportation Institute, Research Report 1131-2, College Station, Texas, Oct. 1989.

[41] Lindley, J., "Urban Freeway Congestion Problems and Solutions: An Update," ITE Journal, Dec. 1989, pp. 21-23. Feng, An, "Automobile Fuel Economy and Traffic Congestion," Dissertation for PhD in Applied Physics, University of Michigan, 1992. Westbrook, F. and Patterson, P., "Changing Driving Patterns and Their Effect on Fuel Economy," presented May 2, 1989 at the 1989 SAE Government/Industry Meeting, Washington, D.C.

Table F-24. Congestion Index Value for Selected Cities

Urban Area	Freeway/Expressway Streets		Principal Arterial		Congestion[3]	
	DVMT[1]	DVMI[2]	DVMT[1]	DVMI[2]	Index	Rank
Western & Southern Cities	4,580	295	16,475	2610	1.23	4
Phoenix AZ	96,890	4,880	73,810	11,780	1.47	1
Los Angeles CA	8,055	660	6,135	1,000	1.00	17
Sacramento CA	23,155	1,640	8,180	1,560	1.08	12
San Diego CA	39,580	2,305	12,670	2,005	1.31	2
Denver CO	9,550	830	10,600	1,930	0.95	22
Miami FL	7,420	555	13,000	2,000	1.14	7
Tampa FL	3,300	280	3,880	610	1.02	16
Atlanta GA	23,940	1,600	9,350	1,500	1.16	6
Indianapolis IN	7,640	710	4,100	835	0.85	32
Louisville KY	5,380	515	2,975	520	0.86	30
Kansas City MO	11,920	1,410	4,350	910	0.69	39
St. Louis MO	16,290	1,430	11,215	1,745	0.96	20
Albuquerque NM	2,025	200	3,550	650	0.91	26
Oklahoma City OK	6,330	700	3,465	655	0.76	36
Portland OR	6,700	540	3,200	525	1.00	17
Memphis TN	3,730	375	3,930	760	0.84	34
Nashville TN	5,000	430	4,915	905	0.95	22
Salt Lake City UT	3,810	410	1,865	340	0.78	35
Seattle-Everett WA	16,600	1,140	8,950	1,475	1.14	7
Northeast & Midwest Cities						
Washington DC	22,910	1,555	18,400	2,240	1.25	3
Chicago IL	30,945	2,260	24,965	3,870	1.11	9
Baltimore MD	13,735	1,200	9,020	1,680	0.92	25
Boston MA	20,205	1,490	13,700	2,675	1.04	14
Detroit MI	21,800	1,610	21,545	3,450	1.10	11
Minn-St. Paul MN	15,620	1,230	5,200	1,160	0.97	19
New York NY	73,615	5,385	46,490	6,930	1.11	9
Cincinnati OH	9,560	845	3,315	790	0.87	29
Cleveland OH	11,185	960	4,840	1,100	0.89	27
Philadelphia PA	15,125	1,370	22,550	3,150	1.06	13
Pittsburgh PA	7,190	925	9,905	1,510	0.85	32
Milwaukee WI	6,820	570	4,640	930	0.94	24
Major Texas Cities						
Austin TX	5,150	420	2,150	415	0.96	20
Corpus Christi TX	1,500	180	1,490	320	0.72	37
Dallas TX	22,100	1,640	8,200	1,690	1.03	15
El Paso TX	3,200	345	3,000	805	0.72	37
Fort Worth TX	11,000	990	4,250	840	0.88	28
Houston TX	25,800	1,640	10,500	1,970	1.19	5
San Antonio TX	8,800	810	4,800	1,050	0.86	30
Westbrook Avg	15,095	1,045	9,750	1,715	1.01	
North/Midwest Avg	20,725	1,615	15,380	2,455	1.01	
Outside TX Avg	17,205	1,260	11,860	1,995	1.01	
Texas Avg	11,080	860	4,910	1,015	0.91	
Congested TX Avg	14,570	1,100	5,980	1,195	0.98	
Total Avg	16,105	1,190	10,610	1,820	0.99	
Maximum Value	96,890	5,385	73,810	11,780	1.47	
Minimum Value	1,500	180	1,490	320	0.69	

Note: Congested Texas cities average includes Austin, Dallas, Fort Worth, Houston, and San Antonio.

[1]Daily vehicle-miles of travel

[2]Daily vehicle-miles of travel per lane-mile

[3]See Equation a-1

Table F-25. 1987 Urban Area Rankings by Congestion Index and Cost per Capita

Urban Area	Congestion Index		Congestion Cost per Capita	
	Value	Rank	Value (Dollars)	Rank
Western & Southern Cities				
Phoenix AZ	1.23	4	510	10
Los Angeles CA	1.47	1	730	2
Sacramento CA	1.00	17	360	19
San Diego CA	1.08	12	280	25
San Fran-Oakland CA	1.31	2	670	3
Denver CO	0.95	22	420	14
Miami FL	1.14	7	670	4
Tampa FL	1.02	16	340	22
Atlanta GA	1.16	6	650	5
Indianapolis IN	0.85	32	100	38
Louisville KY	0.86	29	180	31
Kansas City MO	0.69	39	130	35
St. Louis MO	0.96	20	380	17
Albuquerque NM	0.91	26	250	27
Oklahoma City OK	0.76	36	170	34
Portland OR	1.00	18	300	24
Memphis TN	0.84	34	210	29
Nashville TN	0.95	23	380	18
Salt Lake City UT	0.78	35	120	36
Seattle-Everett WA	1.14	8	580	6
Northeast & Midwest Cities				
Washington DC	1.25	3	740	1
Chicago IL	1.11	9	340	21
Baltimore MD	0.92	25	340	23
Boston MA	1.04	14	400	16
Detroit MI	1.10	11	480	11
Minn-St. Paul MN	0.97	19	240	28
New York NY	1.11	9	430	12
Cincinnati OH	0.87	29	180	32
Cleveland OH	0.89	27	170	33
Philadelphia PA	1.06	13	520	9
Pittsburgh PA	0.85	32	410	15
Milwaukee WI	0.94	24	190	30
Major Texas Cities				
Austin TX	0.96	21	420	13
Corpus Christi TX	0.72	37	80	39
Dallas TX	1.03	15	530	8
El Paso TX	0.72	37	110	37
Fort Worth TX	0.88	27	360	20
Houston TX	1.19	5	550	7
San Antonio TX	0.86	30	260	26

Source: Hanks, J., and Lomax, T., Roadway Congestion in Major Urban Areas: 1982 to 1987, TTI, Research Report 1131-2, College Station, TX, Oct. 1989.

Lindley's projections of consumption statistics for the year 2005 take into account factors including time delays, wasted fuel, and user cost. The urban freeway congestion statistic projections developed by Lindley are presented in Table F-26.

The projections generated in this study utilize the wasted fuel values developed by Lindley as the basis to measure the impact of urban congestion on the fuel efficiency gap. The study further assumes that the amount of wasted fuel due to congestion will increase following a logistic trend.

The amount of wasted fuel is divided between automobiles and light duty trucks assuming that the light duty trucks VMT driving share will increase from 23.4 percent in 1989 to 33 percent in 2010, and will remain constant at 33 percent through 2030.

Automobiles:
The wasted fuel forecast due to traffic delays for the year 2010 is 9,164 mil.gal. and for the year 2030 it is 11,426 mil.gal. as summarized in Table F-27. This implies that the fuel efficiency gap will be 18.66 percent in 2010 and 23.08 percent in 2030. These are lower projections as compared to the unadjusted figures of 21.53 percent and 26.32 percent corresponding to the same years.

Light Duty Trucks:
Table F-28 presents the fuel efficiency gap projections for light duty trucks based on adjusted city/highway shares and assuming logistic growth of wasted fuel due to congestion. The wasted fuel forecast for light duty trucks for the year 2010 is 4,513 mil.gal. and for the year 2030 it is 5,628 mil.gal. This implies that the fuel efficiency gap will be 32.77 percent in 2010 and 33.43 percent in 2030 as compared to the unadjusted figures of 32.91 percent and 34.09 percent.

Overall Degradation Factor Forecast

Figures F-7 and F-8 summarize the projections of the fuel efficiency gap using assumptions of logistic growth and adjusted city/highway shares for automobiles and light duty trucks, respectively. The overall results are listed in Table F-29.

As illustrated in Table F-29, the logistic approach generates lower forecasts for the overall fuel efficiency gap for both automobiles and light duty trucks as compared to the ones generated using the linear approach. The overall fuel efficiency gap for automobiles is expected to increase from a base of 15.2 to 27.00 by the year 2030 assuming a logistic trend. The fuel efficiency gap will

increase further to 34.07 if a linear trend is assumed instead. The overall fuel efficiency gap for light duty trucks is expected to increase from a base of 28.3 to 37.85 or 42.91 by the year 2030 assuming logistic and linear growth respectively.

Table F-26. Urban Freeway Congestion Statistics

	1984	1987	(1984 data) 2005	(1987 data) 2005
Freeway Miles	15335	16097	15335	16097
Vehicle-Miles of Travel (billions)	277	337	411.0	493
Recurring delay (million vehicle-hours)	485	728	2049	3030
Delay due to incidents (million vehicle-hours)	767	1287	4858	7978
Total delay (million vehicle-hours)	1252	2015	6907	11008
Total wasted fuel (million gallons)	1378	2206	7317	11638
Total user costs (billion dollars)	9	16	51	88

Source: Lindley, J., "Urban Freeway Congestion Problems and Solutions: An Update," ITE Journal, December 1989, pages 21-23.

Table F-27. Automobile Fuel Efficiency Gap Projections: Logistic Increasing Congestion Trend (with Adjusted City/Highway Driving Share)

	1990	1995	2000	2005	2010	2015	2020	2025	2030
Wasted Fuel (Million Gallons)	2252	3865	5788	7764	9164	10284	10924	11259	11426
Base Gap	15	15	15	15	15	15	15	15	15
Gap Forecast	15.69	16.37	17.34	18.20	18.66	22.08	22.50	22.79	23.08
Change	0.49	1.17	2.14	3.00	3.46	6.88	7.30	7.59	7.88

Figure F-7. Fuel Efficiency Gap for Automobiles (with Adjusted Driving Share)

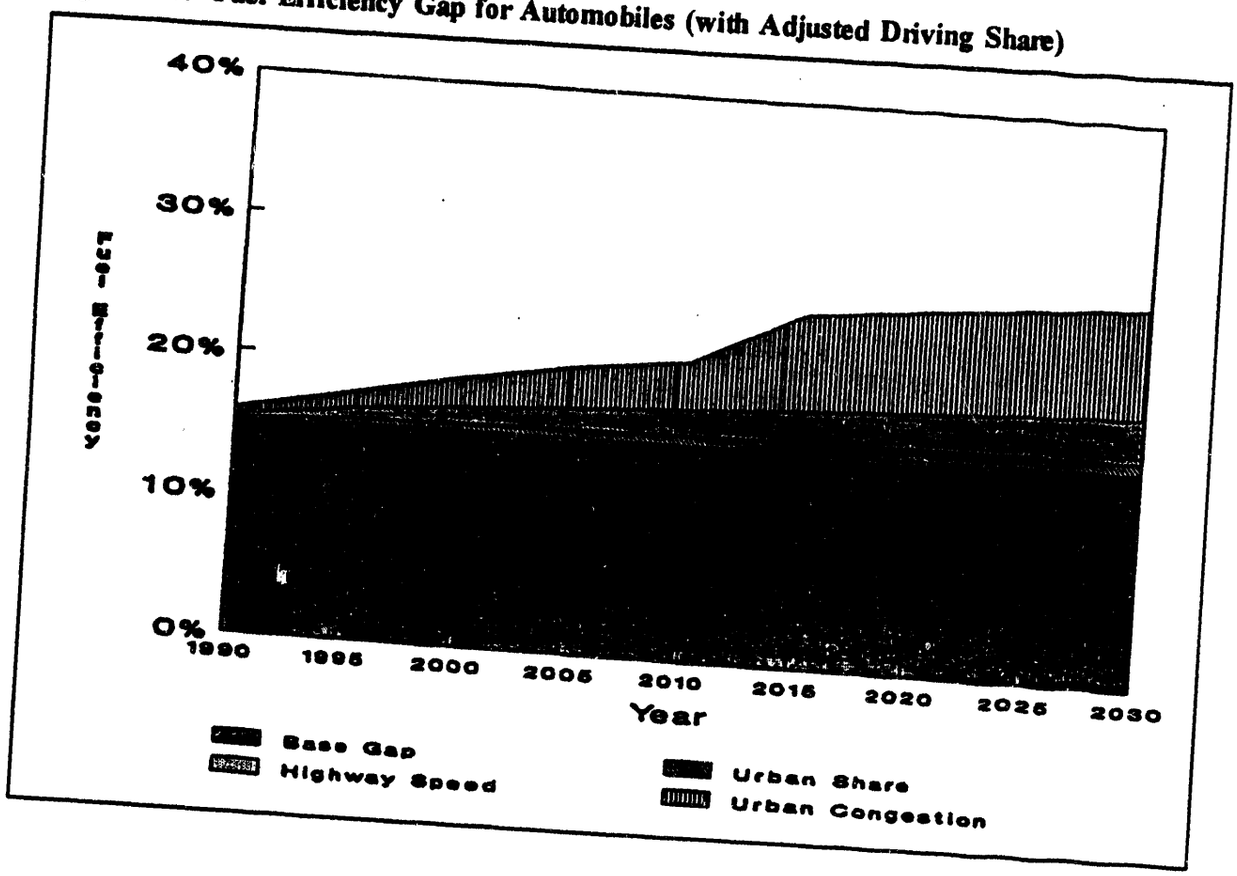


Figure F-8. Fuel Efficiency Gap for Light Duty Trucks (Logistic Forecast)

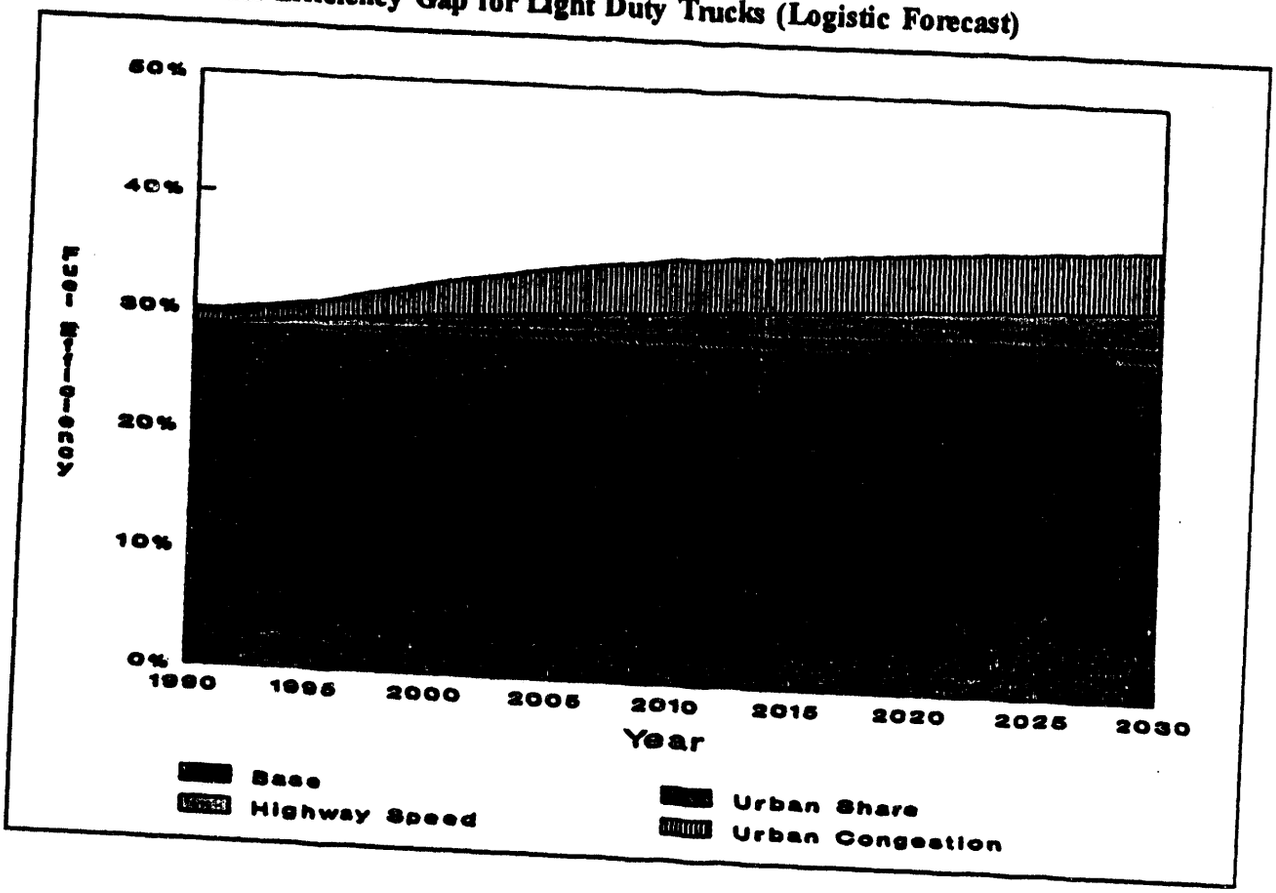


Table F-28. Light Truck Fuel Efficiency Gap Projections: Logistic Increasing Congestion Trend (with Adjusted City/Highway Driving Share)

	1990	1995	2000	2005	2010	2015	2020	2025	2030
Wasted Fuel (Million Gallons)	611	1203	2240	3375	4513	5065	5380	5545	5628
Base Gap	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3	28.3
Gap Forecast	29.41	29.76	31.17	32.17	32.77	32.89	33.14	33.28	33.43
Change	1.11	1.46	2.87	3.87	4.47	4.59	4.84	4.98	5.13

Table F-29. Total Fuel Efficiency Gap Projections for Automobiles and Light Duty Trucks with Adjusted City/Highway Driving Share

	1990	1995	2000	2005	2010	2015	2020	2025	2030
AUTOMOBILES									
Base Gap	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20	15.20
Gap Forecast	15.87	17.42	18.98	20.29	21.18	25.03	25.82	26.43	27.00
Change	0.67	2.22	3.78	5.09	5.98	9.83	10.62	11.23	11.80
L. D. TRUCKS									
Base Gap	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30	28.30
Gap Forecast	29.78	30.83	32.90	34.52	35.59	36.22	36.87	37.35	37.85
Change	1.48	2.53	4.60	6.22	7.29	7.92	8.57	9.05	9.55

Attachment 4: Vehicle-Miles Traveled Model

Development of the VMT Forecasting Model

INTRODUCTION

The following is a description of a new VMT forecasting model which has been developed to replace the approach previously used. This approach addresses two demographic issues which have been shown to influence driving rates:

1. Historically, the proportion of Female VMT to Male VMT has grown steadily. This factor has been an important explanatory variable explaining aggregate VMT growth in the past.

2. The proportion of the population 60 or over (a reasonable proxy for retirement) has remained extremely steady over the period of estimation (1970-1991). This share was approximately 20 percent in 1970 and it was still 20 percent in 1990.

The first item is relatively easy to deal with. Traditional econometric techniques provide an estimate of how total VMT has varied as the proportion of Female to Male VMT has increased. This proportion, however, is not likely to continue to grow as it has in the past. Specifically, it is assumed in the analysis that follows that the Female to Male VMT ratio asymptotically approaches 0.8. This proportion is consistent with several recent Department of Transportation Nationwide Personal Transportation Surveys (NPTS).

The affect of the "aging of the population" on VMT cannot be assessed by analyzing historical data. There has been no variation in the over 60 population share historically, it should not be particularly surprising that attempts to measure the "aging of the population" affect on VMT using econometric techniques have not been very satisfying. In spite of this, there is ample survey data indicating that drivers 60 and over drive substantially less than do younger. The most recent NPTS indicates that those over 60 drive only about half as much as do younger drivers. None of this would affect the accuracy of our aggregate VMT forecast if the proportion of the population 60 and over remained at 20 percent. The Census Department, however, accurately records the inevitable aging of the "baby boom" generation. In the early 2000's they project that the proportion of the population over 60 begins to rise sharply. By 2020, it reaches 30 percent, up from 21 percent in 2000.

Rather than ignore the forecast shift in demographic trends, the methodology described in the following pages explicitly adjusts the forecast based on survey information. In 2015, the total VMT forecast is 3.6 percent lower once the aging of the population is accounted for.

METHODOLOGY

- VMT per capita is considered to be a function of economic and demographic variables.[42] The variables which are considered are as follows:

CPM87, the fuel cost of driving a mile, expressed in 1987 dollars.
YPC87, disposable personal income per capita, expressed in 1987 dollars.
PrFem, the ratio of per capita female driving to per capita male driving.
P>60, the proportion of the population greater than or equal to 60 years of age.

- The following correlation table suggests that multicollinearity between P>60 and YPC87 would result in biased estimators. P>60 is not included in the regression, but there is strong reason to expect the aging of the population to influence driving habits early in the next century. The proposed adjustment factor based on aging will be described below.

Table F-30. VMT Variable Correlation Coefficients

	VMTPC	YPC87	CPM87	PrFem	P>60
VMTPC	1.000	0.961	-0.589	0.783	0.925
YPC87	0.961	1.000	-0.410	0.643	0.947
CPM87	-0.589	-0.410	1.000	-0.803	-0.467
PrFem	0.783	0.643	-0.803	1.000	0.748
P>60	0.925	0.947	-0.467	0.748	1.000

[42] VMT per capita should be understood to mean VMT per population 16 years and older. *Per capita* is used for simplicity. Its use in other variables refers to the total US population.

- The following linear model is tested, using data from 1969-1990:

$$\mathbf{VMTPC} = \alpha + \beta_1 \mathbf{CPM87} + \beta_2 \mathbf{YPC87} + \beta_3 \mathbf{PrFem} \tag{7}$$

The regression provides the following output:

Table F-31. VMT Linear Regression Output

	Constant	CPM87	YPC87	PrFem	D-W	Adj. R-Sq
Parameter	-0.148	-4.878	5.9e-04	4.470	0.925	0.968
T-Stat		-1.574	15.348	2.638		

- The D-W statistic for this model suggests the possibility of serial correlation. A generalized difference equation of the following form is tested, using the Cochrane-Orcutt iterative procedure:

$$\mathbf{VMTPC}_T - \rho \mathbf{VMTPC}_{T-1} = \alpha(1-\rho) + \sum_{N=1}^{3} \beta_N (X_{N,T} - \rho X_{N,T-1}) \tag{2}$$

where $X_{N=1,..,3}$ represent the input variables. This results in the following parameters, which are used to produce an unadjusted forecast of VMTPC:

Table F-32. VMT Generalized Difference Equation Output

	ρ	Constant	CPM87	YPC87	PrFem	Adj. R-Sq
Parameter	0.72	0.28	-7.50	3.6e-04	8.36	0.841
T-Stat			-2.32	2.46	2.99	

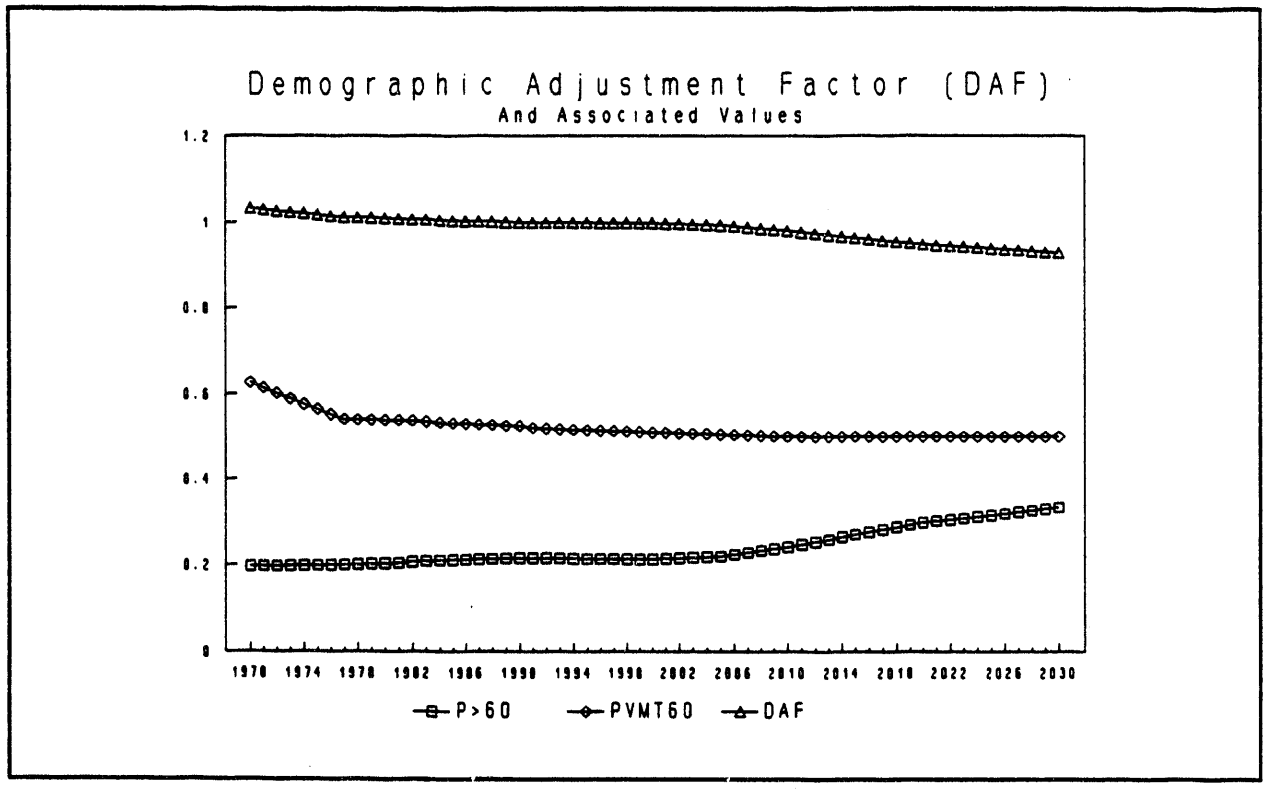
- The unadjusted forecast is subsequently modified by a demographic adjustment factor (DAF). This is an index which is based on projections of the proportion of the population over 60 years of age (P>60) and the expected ratio of per capita driving by those over 60 to those

under 60 (PVMT60). Historical data and projections until 2030 are provided in the graph below. The DAF, also graphed, is calculated as follows:

$$DAF_T = 1 - [P{>}60_T \cdot (1 - PVMT60_T)] \quad (9)$$

The DAF is subsequently indexed to 1.0 in 1990.

Figure F-9. VMT Demographic Adjustment Factor: 1970-2030



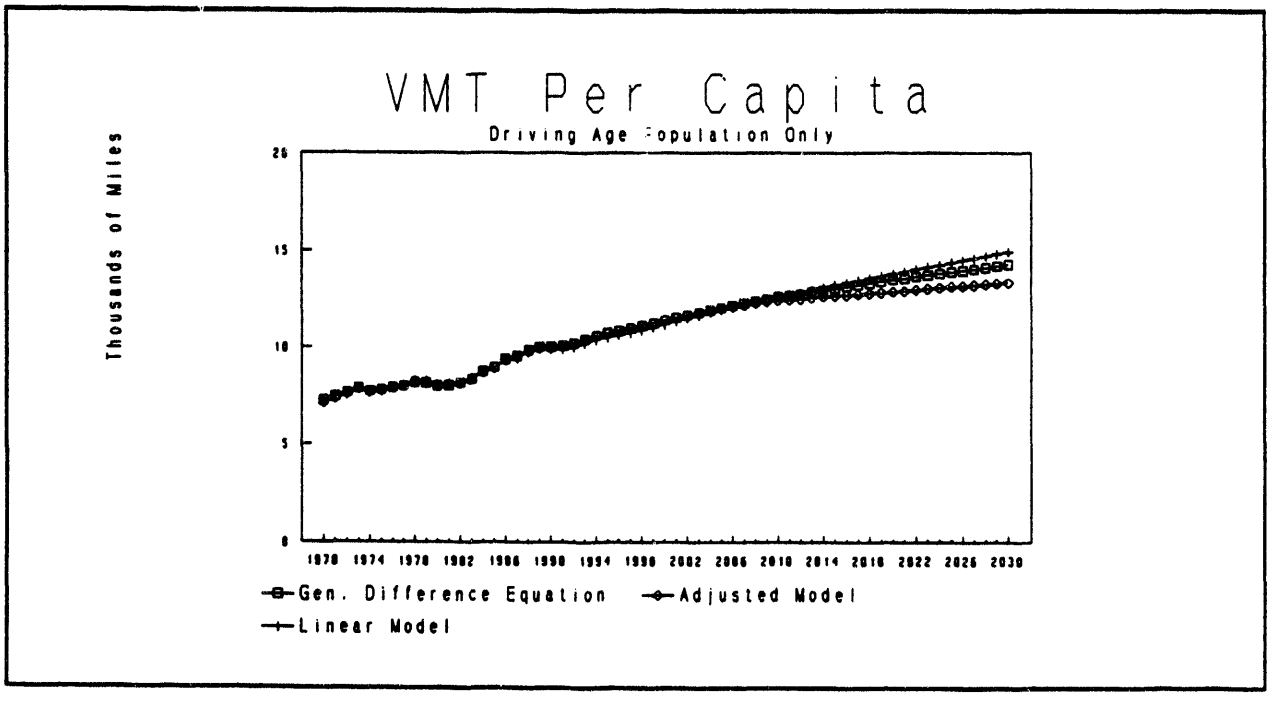
■ The Adjusted VMTPC forecast is the product of the DAF and the unadjusted VMTPC. Figure F-10 presents forecasts of VMTPC made with the original linear equation, the generalized difference equation, and the demographically-adjusted model. Figure F-11 depicts the total VMT forecasts associated with the linear equation and the adjusted difference equation.

■ The average annual growth rates of VMT per capita and total VMT are as follows:

Table F-33. Average Annual VMT Growth Rates

Interval	Adjusted VMT per Capita	Total VMT	
		Linear Model	Adjusted Model
1990 - 2000	1.3%	2.2%	2.2%
2000 - 2010	0.8%	2.0%	1.6%
2010 - 2020	0.3%	1.4%	0.9%
2020 - 2030	0.4%	1.1%	0.7%
1990 - 2030	0.7%	1.7%	1.3%

Figure F-10. VMT Per Capita: 1970-2030



- Point elasticities associated with the difference equation are presented in Figure F-12.

Figure F-11. Linear VMT Projections

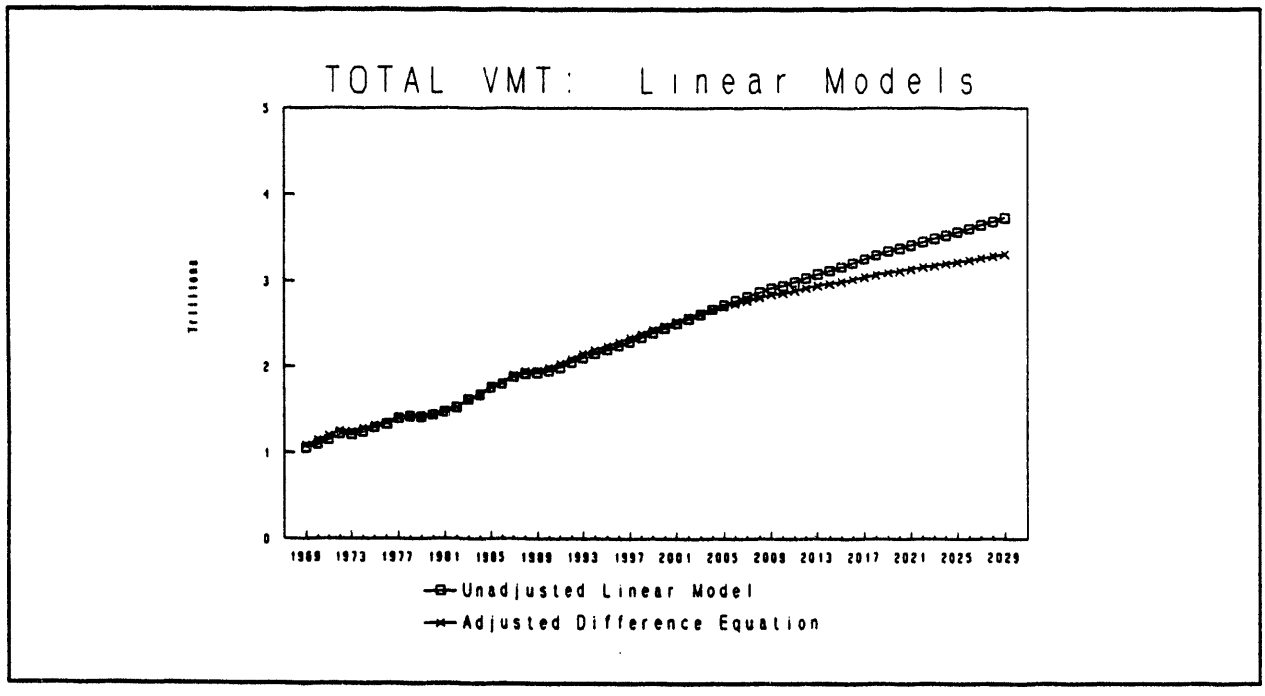
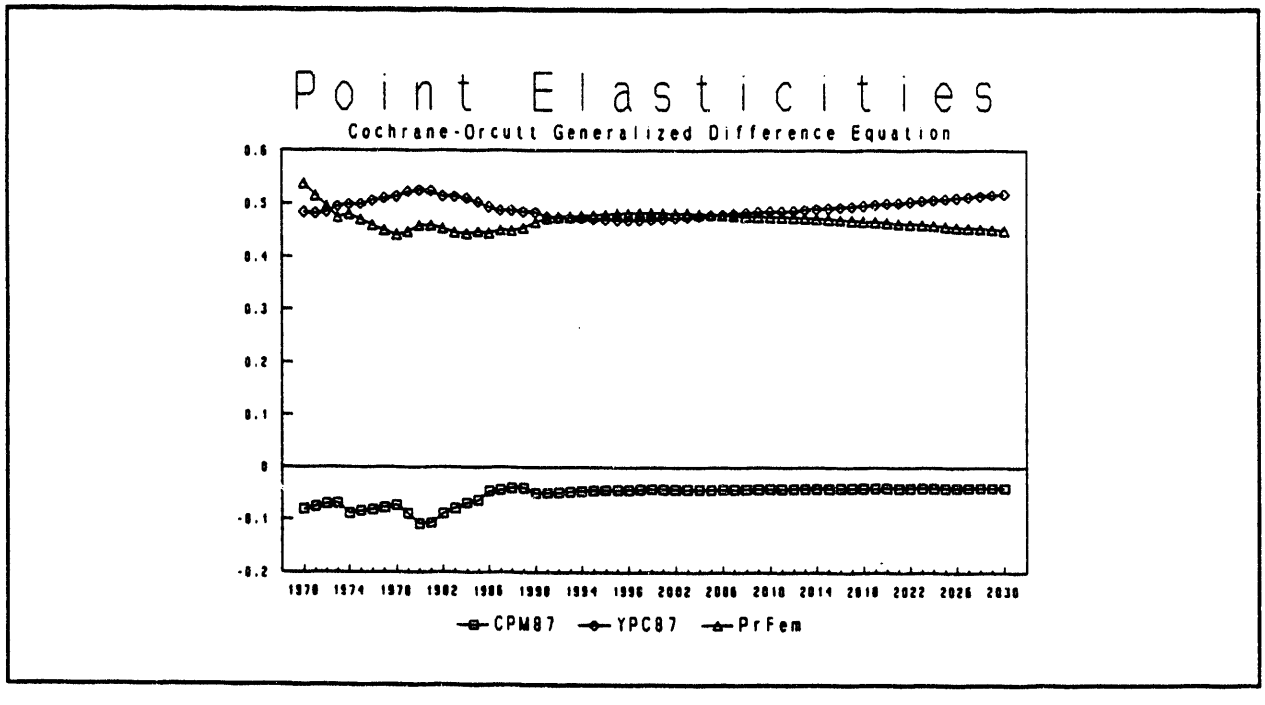


Figure F-12. VMT Point Elasticities: 1970-2030



Attachment 5: Air Travel Module

Derivation of Demographic Adjustment Factors

It is expected that the "personal travel" segment of commercial passenger traffic will be more sensitive to air fares than the "business travel" segment. It is also likely that the volume of discretionary travel will be more influenced by public perceptions of airline safety, convenience, and quality of service. One way of quantifying this effect is in a stratified measure of the "propensity to fly" which, in its most rudimentary form, associates with each age group and gender a static value obtained from a survey of travelers.[43] The propensity to fly is considered to be the product of the percentage of a given population segment to have flown in the previous year, and the average number of flights taken by the travelers. This translates into the number of trips per capita associated with that population cohort. These values are subsequently used to modulate forecasts produced by the conventional model as follows:

$$ARPM_T = DI_T \cdot RPM_{D,P,T} \tag{10}$$

where:

$ARPM_T$ = Adjusted personal-travel revenue passenger miles in year t.
DI_T = Demographic index in year t.
$RPM_{D,P,T}$ = Unadjusted forecast of domestic personal RPM in year t.

and:

$$DI_T = \left[\frac{\sum_I POP_{I,T} \cdot PROFLY_{I,T}}{\sum_I POP_{I,T}}\right] \div \left[\frac{\sum_I POP_{I,0} \cdot PROFLY_{I,0}}{\sum_I POP_{I,0}}\right] \tag{11}$$

where:

$POP_{I,T}$ = The population of the Ith cohort in year T.
$POP_{I,0}$ = The population of the Ith cohort in the base year.
$PROFLY_{I,T}$ = The propensity to fly for the Ith cohort.

The following describes the assumptions and data manipulations undertaken to develop age- and

[43] This adjustment algorithm has been adapted from that provided in Appendix A of *Forecasting Civil Aviation Activity: Methods and Approaches*, Transportation Research Circular Number 372, Transportation Research Board, June 1991.

gender-specific demographic adjustments to forecasts of personal travel. The use of these factors is predicated on the static nature of the public's propensity to fly ($PROFLY_{I,T} = PROFLY_{I,0}$), absent sufficient time series data to reflect and predict changing trends.

■ The ATA travel survey provides the percentage of each age group which has flown in the previous year (π_A), as well as the fraction of men and women of all age groups who have flown (π_M, π_W). The first step is to derive an estimate of the percentage of each age group and sex which has flown.

■ Given that N_M and N_W represent the total number of men and women, respectively, the percent of the flying population that are of each gender can be represented as follows:

$$P_M = \frac{\pi_M N_M}{\pi_M N_M + \pi_W N_W} \quad ; \quad P_W = 1 - P_M \tag{12}$$

Using the 1990 Census numbers, $P_M = 0.53$ and $P_W = 0.47$. In other words, 53 percent of people who took at least one air trip in the previous year were male.

■ It is assumed that this gender ratio is constant across age groups and time. This ratio is used to estimate the percentage of the population by gender and age group which has flown in the previous year. The equation for males is as follows:

$$\pi_{M,A} = \frac{P_M \pi_A N_A}{N_{M,A}} \tag{13}$$

In order to determine the number of trips per capita for male and female cohorts, further assumptions are necessary.

■ According to the ATA survey, male travelers flew more than female travelers; the ratio of male to female trips per capita is 1.72, i.e.:

$$\frac{T_M}{N_M} = 1.72 \frac{T_W}{N_W} \tag{14}$$

where T_M and T_W represent the total number of trips by male and female travellers, respectively.

■ In each age group, the number of average trips per capita is reported. It is assumed that the male/female travel ratio holds across age groups, which enables the subsequent division

of each figure into two gender-specific figures.

For each age group, the number of trips per capita (TPC) is expressed as:

$$\frac{T_{M,A} + T_{W,A}}{N_{M,A} + N_{W,A}} = TPC_A \tag{15}$$

From above:

$$T_{M,A} = 1.72\left(\frac{T_{W,A}\, N_{M,A}}{N_{W,A}}\right) \tag{16}$$

Substituting, and rearranging:

$$T_{W,A}\left(1 + 1.72\left(\frac{N_{M,A}}{N_{W,A}}\right)\right) = TPC_A\,(N_{M,A} + N_{W,A}) \tag{17}$$

which leads to the trips per capita for women, by age group:

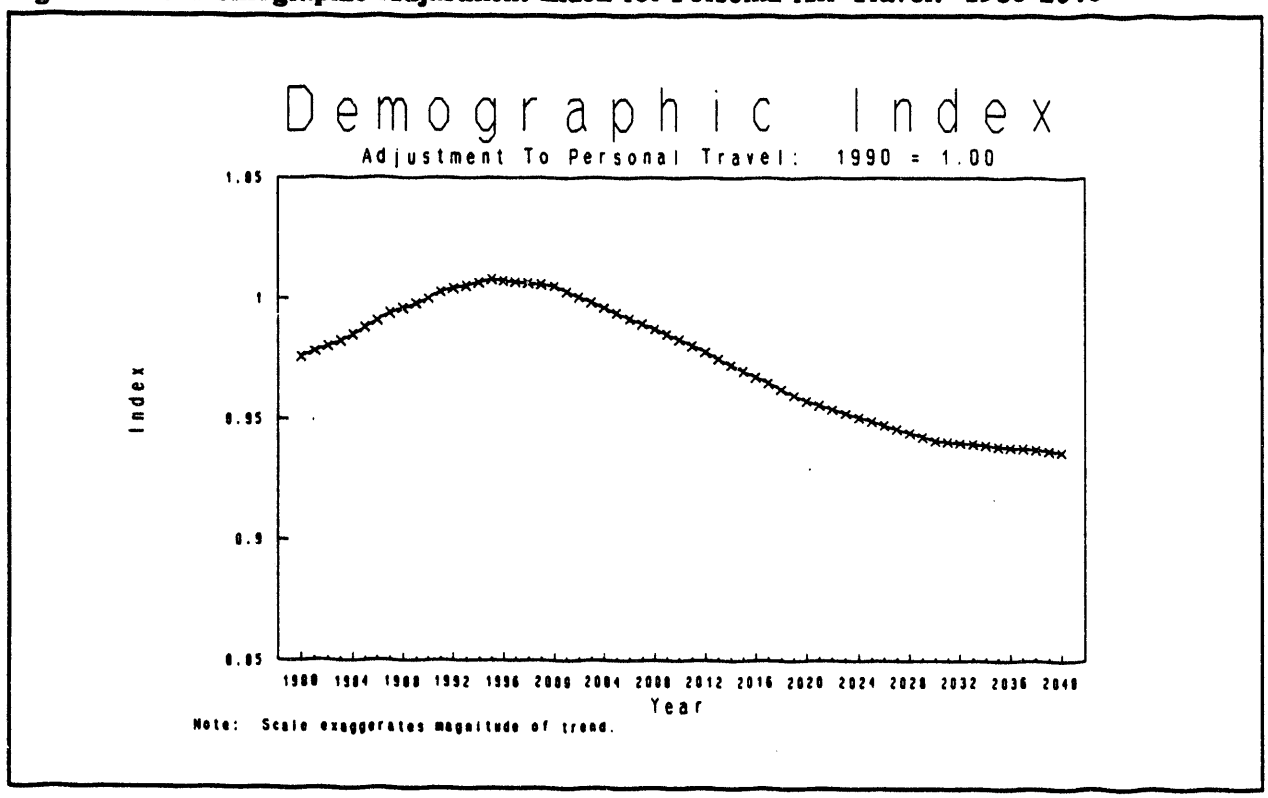
$$\frac{T_{W,A}}{N_{W,A}} = TPC_A\left[\frac{N_{M,A} + N_{W,A}}{N_{W,A} + 1.72\,N_{M,A}}\right] \tag{18}$$

The resultir figures are tabulated, and a graph of the demographic index through the year 2040 is provide on the following page.

Table F-34. ATA 1990 Air Travel Survey Data

Age Group	1990 Population ('000)		Percentage Flown		Average Trips per Capita		Propensity to Fly ($PROFLY_{I,T}$)	
	Male	Female	Male	Female	Male	Female	Male	Female
18-24	13,215	12,925	0.31	0.29	3.29	1.91	1.03	0.55
25-34	22,078	21,848	0.37	0.33	4.88	2.83	1.80	0.94
35-44	18,193	19,112	0.38	0.32	5.18	3.03	1.97	0.97
45-54	12,406	13,081	0.39	0.33	4.82	2.81	1.89	0.93
55-64	10,103	11,260	0.33	0.26	4.17	2.45	1.36	0.63
65+	12,853	18,706	0.31	0.19	4.28	2.52	1.34	0.48

Figure F-13. Demographic Adjustment Index for Personal Air Travel: 1980-2040



Sources:

Population Data: U.S. Department of Commerce, Bureau of the Census, *Projections of the Population of the United States by Age, Sex, and Race: 1988 to 2080,* Population Estimates and Projections, Series P-25, No. 1018.

Percentage Flown & Trips per Capita: ATA, *Air Travel Survey, 1990.*

Attachment 6: Vehicle Emissions Module

Derivation of Emission Factors

INTRODUCTION

This report provides EPA emission factors to be used in the transportation vehicle emission solution algorithm, which is outlined in the *Transportation Sector Component Design Report* (TSCDR) section on emissions. This algorithm is as follows:

$$EMISS_{IE,IM,IR,T} = EFACT_{IE,IM,IR,T} * U_{IM,IR,T}$$

where *EMISS* is total emissions of pollutant IP by mode IM, in region IR, and time T, *EFACT* is an emission factor based on technology, fuel and vintage weights, and *U* is a measure of annual vehicle activity (vehicle-miles-traveled or fuel consumption in gallons).

The TSCDR specifies modal emission factors for SO_x, NO_x, carbon, CO, CO_2 and VOCs, and calls for emissions to be calculated for the following six transportation modes:

Highway	Non-Highway
Light-Duty Vehicles	Rail
Freight Trucks	Air
Buses	Water

A number of these transportation modes have subcomponent modes that are to be handled in a separate TERF "Miscellaneous End-Use Component" module. These subcomponent modes include military aircraft, recreational boating, passenger rail, and buses. This report also provides the emission factors for these miscellaneous transportation energy end-use categories, as well as for alternative fuel vehicles (AFVs).

Pollutant emission factors are not reported for certain transportation vehicles. Reasons for the exclusion of these emission factors include one or more of the following:

- the lack of adequate EPA emissions testing results for the production of reliable fleet-average emission rates,

- the quantities of a pollutant generated a vehicle type are not significant,

- the pollutant is not regulated by the EPA (for example, only aircraft HC and smoke emissions are currently regulated).

Such instances of nonreported emission factors are documented in the relevant transportation mode sections of this report.

HIGHWAY MOBILE SOURCE EMISSION FACTORS

Highway Source Emission Factor Information Sources

Emission factors and the accompanying calculation procedures used for virtually all federal and state mobile source emission inventory studies come from the following EPA source documents:

- *Compilation of Air Pollutant Emission Factors - Volume II: Mobile Sources* (AP-42, Fourth Edition, September 1985)

- *Supplement A to AP-42 Volume II*, January 1991.

- *User's Guide to MOBILE4.1*, EPA-AA-TEB-91-01 (EPA Office of Mobile Sources, Emission Control Technology Division, July 1991).

- *Interim Guidance for the Preparation of Mobile Source Emission Inventories*, Attachments A through J (This EPA memorandum supersedes the mobile source emission inventory preparation instructions contained in *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, which is currently being revised)

- *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, EPA-450/4-81-26d (revised), (July 1992).

The document, *Compilation of Air Pollutant Emission Factors - Volume II*, reports all data and emission factor calculation algorithms for both highway and off-highway emission sources. Supplement A to AP-42 presents updated emissions factor information for highway sources based on the results of additional vehicle test data obtained subsequent to the publication of the original AP-42 Air Pollutant Emission Factor compilation document, as well as methodological modifications reflecting calculation refinements and new emission regulations. Both EPA data source documents categorize highway mobile sources into eight types: light-duty gasoline vehicles (LDGVs), light-duty gasoline-powered trucks with a gross vehicle weight rating of less than or equal to 6,000 lbs (LDGT1s), light-duty gasoline-powered trucks with a gross vehicle weight rating greater than 6,000 lbs (LDGT2s), heavy-duty gasoline-powered vehicles (HDGVs), light-duty diesel-powered vehicles (LDDVs), light-duty diesel-powered trucks (LDDTs), heavy-duty diesel-powered vehicles (HDDVs), and motorcycles. The EPA document, *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, provides the most up-to-date instructions for all state and local agencies involved in the preparation of mobile source inventories. The EPA makes frequent mention of the fact that a number of emission rate studies are ongoing. Therefore, frequent monitoring of the status of EPA analytical studies is suggested in order to ensure that TERF emission factors reflect the latest available emission testing and methodological information.

Highway mobile source emission factor calculation routines, outlined in the above EPA documents, are incorporated into EPA's MOBILE model, which estimates hydrocarbon, carbon monoxide, and oxides of nitrogen emission factors for gasoline and diesel-powered vehicles. The most recent version of the mobile emissions model, MOBILE4.1, was released in 1991 for the express purpose of preparing all 1990 base year emission inventories mandated by the CAAA for all areas exclusive of California, and to prepare CAAA-mandated carbon monoxide emissions inventory projections. However, MOBILE4.1 does not incorporate the effects of other CAAA provisions, such as the Tier I exhaust emissions standards for light-duty vehicles and light-duty trucks. Revisions to the MOBILE4.1 model to reflect CAAA provisions for NMHC and NO_x and additional test data are being discussed and planned for incorporation into the new MOBILE5 model. The EPA is currently seeking recommendations through a series of public workshops, and expects to release MOBILE5 in the fall of 1992. Appendix E.EM.B provides an excerpt from an EPA letter handout (dated March 5, 1992) that outlines potential MOBILE5 revisions.

Highway source emission factors for California are calculated through the use of the California Air Resources Board's own emission factor model, EMFAC. The most recent version of this model is EMFAC7EP, which incorporates the most recent California vehicle and fuel standards. All EMFAC model versions are variants of EPA's MOBILE model, and have been customized

to serve the emission calculation needs of the CARB. EPA's Office of Mobile Sources is currently examining CARB in-use test data for vehicles certified to meet California's 0.7 gpm NO_x emission standard. Emission rate equations for reflecting the effects of California's low-emitting vehicle (LEV) program and inspection/maintenance credits are also being considered for inclusion in MOBILE model updates.

The California Air Resources Board uses a separate computer model to assimilate emission test data and calculate basic emission rates. This model, CALIFAC, uses the CARB's In-Use Surveillance Program and the Inspection/Maintenance Project databases (along with EPA data) to derive the basic emission factors. The basic emission factors serve as the inputs to EMFAC, which subsequently applies emission correction factors to produce final emission factors. This report lists the California highway emission factors along with the EPA national emission factors.

The EPA Procedure for Calculating Mobile Source Emissions Factors

Methodology Overview

Federal and state agency-developed emission factors for each vehicle type are derived from a four-step process[44]:

First, "basic exhaust emission factors", or BEFs, are estimated according to rigid federal testing procedures[45].

Second, the BEFs are adjusted with a series of multiplicative and additive correction factors that account for testing condition variances in ambient temperature and operating mode, as well as expected emission cont^Xxl device tampering rates.

Third, the BEFs are further adjusted with a composite correction factor that reflects actual vehicle characteristics and driver operating practices (For the hydrocarbon BEF, separate emission factors for evaporative and running losses are added. In addition, the hydrocarbon and carbon monoxide BEFs are adjusted for fuel volatility.). A number of

[44] All emission rate equations and data referenced in this section come from EPA's AP-42 document and accompanying supplements, or the MOBILE4.1 model documentation, unless otherwise noted.

[45] Exhaust and evaporative emissions testing procedures for light-duty gasoline and diesel-powered vehicles are stipulated in the Code of Federal Regulations, 40 CFR Part 86, Subpart B, July 1, 1989. Testing procedures for heavy-duty gasoline and diesel-powered vehicles are stipulated in 40 CFR Part 86, Subpart N, July 1, 1989.

these correction factors are not included in the emission factor calculations for diesel-powered vehicles and trucks due primarily to a lack of reliable data.

Fourth, consolidated BEFs are derived by weighting the adjusted BEFs according to the fraction of total miles driven for each model year, and then summing over the 25 historical model years that constitute the in-use vehicle fleet for each calendar year.[46] The equations for the consolidated emission factors are as follows:

$$EFHC = \Sigma\, TF * [(ADJBEF * SALHCF * RVPCF) + REFUEL + RNGLOS + CCEVRT]$$
$$EFCO = \Sigma\, TF * (ADJBEF * SALHCF * RVPCF)$$
$$EFNO_x = \Sigma\, TF * (ADJBEF * SALHCF)$$

where:

ADJBEF = Adjusted basic exhaust emission factor in grams per mile,
SALHCF = Composite speed, air conditioning, extra load, and trailer towing correction factor,
RVPCF = Fuel volatility correction factor,
REFUEL = Refueling hydrocarbon emission factor (g/mile),
RNGLOS = Running loss hydrocarbon emission factor (g/mile),
CCERVT = Crankcase and evaporative hydrocarbon emission factor (g/mile),
TF = Fraction of total miles driven

(Summation occurs over 25 model years *i*, from n-24 to n, where *n* is the calendar year)

Methodology Details

Federal Test Procedures. The federal test procedures calculate basic exhaust and evaporative emissions for each vehicle model under specified ambient temperature and humidity levels, average speed and idle time, vehicle-miles-traveled (VMT), percent of VMT in cold-start, hot-start, and stabilized operations, trip length, and fuel volatility.[47] The gathering of exhaust emissions data is accomplished with three test segments. For Segment No. 1 (cold-start test), emissions for the first 505 seconds after engine start-up are collected. For Segment No. 2 (stabilized test), emissions are collected for the next 870 seconds. Finally, for Segment No. 3

[46] The number of model years for the in-use fleet was expanded from 20 to 25 with the release of MOBILE4.1 (see User's Guide to MOBILE4.1, Sec. 1.1.4.).

[47] The measure of volatility is *Reid Vapor Pressure*. Vapor pressure measures the level of surface pressure in pounds per square inch (psi) required to keep a liquid from vaporizing. Vehicles are tested at a certified RVP of 9.0 psi.

(hot-start test), the engine is turned off for a ten-minute duration, and is restarted and run for an additional 505 seconds with emissions being collected. The EPA conducts the test cycles at both low and high altitude locations.

Basic Emission Rates. The basic emission rate is calculated by a two-step formula based on the assumption that emission rates increase linearly with respect to accumulated vehicle mileage. First, a zero-mile emission level is obtained from the in-use vehicle testing results for a specific model year and pollutant. Added to this basic emission rate is an adjustment that reflects the culmulative mileage for the model year vehicle and a per-10,000 mile emission deterioration rate. The two step formula accounts for vehicles with cumulative mileage of less than 50,000, and vehicles with mileage in excess of 50,000. The following example shows the equations and calculations used to obtain basic carbon monoxide emission rates for light-duty vehicles with a 1990 model year.

Basic Emission Factor Adjustments. The basic emission factors are adjusted with a series of general and pollutant-specific correction factors to account for ambient and vehicle operation characteristics that differ from the standardized federal testing conditions. The adjusted BER equations are as follows:

$$ADJBEF_{HC} = \{[(BER * OMTCF) - OFFMTH] * PCLEFT\} + OMTTAM$$
$$ADJBEF_{CO} = (BER * OMTCF * PCLEFT) + OFFCO + OMTTAM$$
$$ADJBEF_{NOx} = (BER * OMTCF) + OMTTAM$$

Example 1: Calculating Carbon Monoxide Base Emission Rates

BER Two-Step Formula

$$BER = ZML + (DR1 * M), \quad \text{for } M \leq 50{,}000 \text{ Miles}$$
$$= ZML + (DR1 * 5) + (DR2 * (M - 5)), \quad \text{for } M \leq 50{,}000 \text{ Miles}$$

where

ZML =	Zero-mile emission level in gpm
DR1 =	Emission deterioration rate for vehicles with less than or equal to 50,000 miles, in gpm per 10,000 miles
DR2 =	Emission deterioration rate for vehicles with more than 50,000 miles, in gpm per 10,000 miles
M =	Model year cumulative mileage divided by 10,000 miles

Assumptions:

(1) CO emissions are for light-duty gasoline-powered vehicles with a 1990 model year
(2) Tests conducted at low altitude
(3) Calculate emission levels at cumulative mileage intervals of 50,000 and 100,000 miles.

50,000 Mile Emission Level:

$$BER = 2.813 + (0.769 * 5) = 6.658 \text{ grams per mile CO}$$

100,000 Mile Emission Level:

$$BER = 2.813 + (0.769 * 5) + (0.961 * (10 - 5)) = 11.463 \text{ grams per mile CO}$$

Data Source: U.S. Environmental Protection Agency Office of Mobile Sources, *Supplement A, Compilation of Air Pollutant Emission Factors, Volume II - Mobile Sources* (AP-42), January 1991.

The equation terms are described below:

Temperature/Operating-Mode Correction Factor (OMTCF) — This multiplicative correction factor accounts for the observation that vehicles produce a smaller quantity of emissions as they move from cold-start to stabilized and hot-start operating modes. The OMTCF is expressed as a sum of VMT-weighted linear functions of the fleet cumulative mileage for each model year, adjusted for (1) the emissions contribution attributable to each operating mode (represented as intercept and slope coefficients of the linear functions), and (2) a previously estimated temperature correction factor for each model year, pollutant, test segment, and ambient temperature (not applicable to diesel-powered

vehicles and trucks). As with the basic emission rate formula, OMTCFs are calculated with a two-stage formula to reflect emissions deterioration for vehicles with cumulative mileage greater than 50,000 miles:

$$OMTCF = (TERM1 + TERM2 + TERM3) / DENOM$$

	Cumulative Mileage ≤ 50,000	Cumulative Mileage > 50,000
TERM1 =	$W * TCF_1 * [B_1 + (D_{11} * M)]$	$W * TCF_1 * [B_1 + (D_{11} * 5)] + [D_{12} * (M - 5)]$
TERM2 =	$(1-W-X) * TCF_2 * [B_2 + (D_{21} * M)]$	$(1-W-X) * TCF_2 * [B_2 + (D_{21} * 5)] + [D_{22} * (M - 5)]$
TERM3 =	$X * TCF_3 * [B_3 + (D_{31} * M)]$	$W * TCF_3 * [B_3 + (D_{31} * 5)] + [D_{32} * (M - 5)]$
DENOM =	$B_0 + (D_{01} * M)$	$B_0 + (D_{01} * 5) + [D_{02} * (M - 5)]$

where:

W =	fraction of vehicle-miles-traveled in the cold start mode
X =	fraction of vehicle-miles-traveled in the hot start mode
TCF_i =	high or low temperature correction factor (depending on ambient testing temperature) for pollutant, model year, and test segment "i"
B_i =	normalized intercept coefficient for pollutant, model year, and test segment "i"
D_{ij} =	normalized slope coefficient for pollutant, model year, test segment "i" and culmulative mileage level "j" (1 if M ≤ 5; 2 if M > 5)
M =	cumulative mileage divided by 10,000 miles for each model year

The low temperature correction factor is applied when the ambient temperature is lower than the reference test temperature of 75°F. For all pollutants, test segments, and model years, *except* segment 1 (cold start) CO emissions for model years from 1980 and later, a simple exponential model is used.[48] In the case of cold start carbon monoxide OMTCFs for model years 1980 and later, two additional calculation steps are necessary. First, TCF_1 is removed from the TERM1 equation in order to eliminate the temperature correction related to the cold start mode. Second, an alternative additive version of the low temperature correction factor is calculated, the "CO offset" (OFFCO), which adjusts the cold start emissions for higher CO produced during the cold start mode. The CO offset is multiplied by the percent of VMT in the cold start mode (the "W" term) and adjusted for fuel volatility if the temperature is greater than 40°F. The CO offset term

[48] The equation is: $TCF_{low} = EXP\ [TC_{ibp} * (T - 75.0)]$, where TC_{ibp} is a coefficient for model year *i*, pollutant *p*, and test segment *b*, at the ambient reference temperature of 75 degrees Fahrenheit; and T is the ambient temperature.

is then added to the basic CO exhaust emission rate factor.

The high temperature correction factor equation for pre-1980 model years, applied when the ambient temperature is higher than 75°F, is similar to that of the low temperature correction factor. For post-1979 model years, an alternative correction factor is used that incorporates a fuel volatility correction component. The combined high temperature/fuel volatility correction factor model is:

$$TRCF = e^{\{[A * (RVP - 9.0)] + [B * (T - 75.0)] + [C * (RVP - 9.0)] * (T - 75.0)\}}$$

where RVP is the fuel volatility level in psi RVP, T is the ambient temperature, and A, B, and C are estimated coefficients.

Tampering Offset (TAMPOFF) — A tampering and misfueling offset (in grams per mile) is added to the basic emission rate to reflect the assumption that a certain fraction of flHxt vehicles have had emission control components disabled or fueling components damaged. Such tampering and misfueling occurrences increase exhaust and evaporative emissions. Tampering/misfueling types tracked by the EPA include air pump disablement, catalyst removal, EGR system disablement, filler neck damage, fuel tank misfueled, combined filler neck damage and fuel tank misfueled, PCV system disablement, canister disconnection, and combined canister and fuel cap removal.

The EPA has conducted nationwide tampering/misfueling surveys since 1978, and data for surveys completed in 1984, 1985, and 1986 have been incorporated into the Tampering Offset calculation methodology.[49] The TAMPOFF is applied to only four vehicle types due to the lack of comprehensive data: light-duty gas-powered vehicles, light-duty gas-powered trucks (both weight categories I and II), and heavy-duty gas-powered vehicles. The TAMPOFFs for each tampering type are calculated with the following equation for calendar year $_n$:

$$TAMPOFF = TAMP_{ipm} * PEQUIP_{im} * RATE_{im}$$

[49] Source: *Compilation of Air Pollutant Emission Factors, Volume 2 — Mobile Sources, Supplement A*, Appendix E, p. E-1. Additional survey results gathered after the publication of this document are also included in the offset estimation equations.

where:

$TAMP_{ipm}$ =	incremental increase in emissions from tampered vehicles for model year *i*, pollutant *p*, and tampering type *m*,
$PEQUIP_{im}$ =	percent of the model-year *i* vehicles that are equipped with item *m* that can be tampered,
$RATE_{im}$ =	percent of model-year *i* vehicles with equipment *m* that has been tampered with.

The term, TAMP, is derived from linear regression equations with cumulative mileage in 10,000-mile increments serving as the regressor or explanatory variable (the regression intercept is interpreted as the zero-mileage emission rate). The regressions yield deterioration rates up to 50,000 cumulative mileage, with mileage in the 50,000 to 130,000 range handled with an additional adjustment factor representing each tampering-type/vehicle-type combination.

The tampering-type emissions offsets are combined to form an overall composite offset with each tampering-type offset adjusted with the applicable temperature correction factor (TCF), and weighted according to the percent of accumulated vehicle-miles-traveled in cold start, stabilized, and hot start modes. The tampering offset is not applicable to diesel-powered vehicles and trucks.

Inspection and Maintenance (I/M) Program Exhaust Emission Benefit (PCLEFT) — This optional emissions rate adjustment factor accounts for the hydrocarbon and CO emissions reduction benefits attributable to inspection/maintenance programs. The emission rate I/M credits are estimated using a separate EPA model, TECH IV+, which is currently being updated into a TECH 5 version that will include a NO_x benefit submodel and other revisions reflecting new I/M program data.[50] I/M program parameters for the TECH model include program start year, stringency level, first/last model years of vehicle subject to program requirements, waiver rates, compliance rates, program type, inspection frequency, vehicle type, test type, and availability of alternative I/M credits for certain technology groups. The I/M program emissions benefit is not applicable to diesel-powered vehicles and all truck types.

Methane Offset (OFFMTH) — This grams-per-mile offset is used to adjust the hydrocarbon basic emission rate when nonmethane HC emissions are estimated. Model-

[50] The only NO_x reduction benefit currently modeled is from a reduction in tampering rates resulting from I/M programs. EPA analysis of transient I/M test (IM240) data indicates that additional emissions reductions result from NO_x cutpoint I/M programs. (See Appendix E.EM.C, List of Potential Revisions for MOBILE5, Item No. 3-5.)

year offsets are calculated for each of the three test segments.

The BEFs are further adjusted by a *composite speed, air conditioning, extra load, and trailer towing correction factor* (**SALHCF**), with the following form:

$$SALHCF_{HC,CO} = SCF * ACCF * XLCF * TWCF$$

and

$$SALHCF_{NOx} = SCF * ACCF * XLCF * TWCF * HCF$$

Each of the equation terms are described below.

Speed Correction Factor (SCF) — Federal test procedures call for the collection of basic exhaust emissions at an average speed of 19.6 miles per hour. To account for higher and lower average speeds exhibited by in-use vehicles, correction factors for three speed ranges were calculated using linear regression.[51] The ranges are low speeds (2.5 to 19.6 mph), moderate speeds (19.6 to 48 mph), and high speeds (48 to 65 mph). The speed correction factors are delineated by model year group, technology, pollutant, and emission level (i.e., normal vs high emitters), but are weighted and combined into one basic speed correction factor applied to base emission rates.

Air Conditioning Correction Factor (ACCF) — The air conditioning correction accounts for the impact of air conditioner operations on pollutant emission types at various ambient temperatures for each model year (This factor is not applicable to heavy-duty gas-powered vehicles, light-duty diesel-powered vehicles, light-duty diesel-powered trucks, and heavy-duty diesel-powered vehicles). The correction factor is expressed as a linear relationship to temperature, adjusted with a multiplicative factor that reflects the fraction of AC units in use. The air conditioning correction factor equation has the following form:

$$ACCF = V * U * [A + (B * (T - 75) - 1)] + 1$$

where:

V = fraction of vehicles equipped with AC,

U = faction of AC units in use = (DI - 70)/10, where DI is the temperature discomfort index,

DI = ((DB + WB)*0.4) + 15,

DB = dry bulb temperature,

[51] The speed correction factors are normalized to the speed associated with a weighted sum of the cold start and hot start mode VMT fractions. The SCFs were derived from multiplicative linear regression equations.

WB = wet bulb temperature,
A = intercept coefficient,
B = slope coefficient,
T = ambient temperature.

Extra Load Correction Factor (XLCF) — This correction factor incorporates the impacts on emissions of an increase of 500 pounds to the test standard vehicle weight, which includes a driver and one passenger. (This factor is not applicable to heavy-duty gas-powered vehicles, light-duty diesel-powered vehicles, light-duty diesel-powered trucks, and heavy-duty diesel-powered vehicles). The extra load correction factor equation is:

$$XLCF = [(XLC - 1.0) * U] + 1.0$$

where XLC is a factor coefficient for each model year and pollutant,[52] and U is the fraction of vehicle-miles-traveled with the extra load.

Trailer Towing Correction Factor (TWCF) — The trailer towing correction factor, which accounts for the effect on emissions of an extra trailer weight of 1,000 pounds, is calculated with an equation that is identical in structure to that used for calculating the extra load correction factor:

$$TTCF = [(TTC - 1.0) * U] + 1.0$$

where TTC is a factor coefficient for each model year and pollutant,[53] and U is the fraction of vehicle-miles-traveled with the extra trailer load.

This factor is not applicable to heavy-duty gas-powered vehicles, light-duty diesel-powered vehicles, light-duty diesel-powered trucks, and heavy-duty diesel-powered vehicles.

NO_x Humidity Correction Factor (HCF) — NO_x emission factors are normalized to 75 grains of water per pound of dry air. To achieve this normalization given various

[52] For example, XLC varies from 1.0786 to 1.0455 for low altitude light-duty gas-powered vehicles, depending on the model year. The XLC range for CO is 1.3058 to 1.1347, and the range for NO_x is 1.0719 to 0.9535.

[53] For example, TTC varies from 1.7288 to 1.2614 for low altitude light-duty gas-powered vehicles, depending on the model year. The TTC range for CO is 1.8940 to 3.9722, and the range for NO_x is 1.1184 to 1.3875.

humidity levels, a multiplicative correction factor is applied to the composite NO_x SALHCF. The following HCF equation is applicable for all model years:

$$HCF = 1.0 - 0.0038 * (H - 75.0)$$

where H = humidity level in grains of water/lb. dry air. This humidity correction factor is not applicable to heavy-duty diesel-powered trucks.

Data obtained from monitoring emissions at different Reid Vapor Pressure levels shows that hydrocarbon and CO emissions increase as volatility increases. For exhaust emissions at fuel volatility levels different from the test certification RVP of 9.0 psi, and when the ambient temperature is greater than 40°F, a *fuel volatility correction factor* (RVPCF) is applied to the basic hydrocarbon and CO emission factors.

There are three fuel volatility correction factor equations, with the selection based on vehicle model year and ambient temperature. For model years 1971 through 1979 (and at all temperatures), the RVPCFs for hydrocarbons and CO are based on a simple linear extrapolation model[54]:

$$RVPCF_{HC} = (0.56222 + 0.012512 * RVP) / 0.67483$$
$$RVPCF_{CO} = (7.1656 + 0.33413 * RVP) / 10.17277$$

For post-1979 model years and at a temperature greater than 75°F, the RVPCF is incorporated with the high temperature correction factor discussed in the Temperature/Operating-Mode Correction Factor (OMTCF) section.

For post-1979 model years and at a temperature in the 40°F to 75°F range, a two-step correction procedure is used. First, a RVP correction factor evaluated at 75°F is obtained using the combined high temperature/fuel volatility model. The resulting RVPCF is then used as an input to the following equation:

$$RVPCF = = 1.0 + \{[(RVPCF_{75°F} - 1.0) * [(T - 40.0) / 35.0)]\}$$

where T is the ambient temperature in the range of 40°F to 75°F.

[54] The denominator value represents the numerator evaluated at the certification Reid Vapor Pressure of 9 psi.

The post-1979 model year fuel volatility correction factors are also disaggregated based on test segment and fuel delivery system (carbureted, throttle-body fuel injection, and multi-point fuel injection).

Evaporative Emissions Factors. In addition to the basic exhaust emission factors for hydrocarbons, evaporative emissions from carburetion and fuel tank systems must be included in the consolidated hydrocarbon emission factors. The EPA models five types of HC evaporative emissions: *crankcase*, *hot soak* (evaporative emissions occurring after a trip), *diurnal* (release of fuel vapors due to an expansion of the air-fuel mixture in a partially filled fuel tank when the ambient temperature increases), *running loss* (emission generated during vehicle operation), and *refueling* (displacement of fuel vapor from the tank during refueling, and spillage). Evaporative emission factors are not applicable to diesel-powered vehicles and trucks.

Crankcase, hot soak, and diurnal emissions (CCERVT) are calculated with one equation:

$$CCERVT = [(HS + TAMPHS) * TPD_j] + [(DI + TAMPDI) / MPD_j] + (CC + TAMPCC)$$

where:

HS = Hot soak emission rates in grams per trip, corrected for temperature and RVP fuel volatility,
TAMPHS = Excess hot soak emission rates due to tampering, corrected for RVP fuel volatility,
TPD_j = Trips per day for age *j* vehicles,
DI = Diurnal emission rates in grams, corrected for temperature and fuel volatility,
TAMPDI = Excess diurnal emission rates due to tampering, corrected for temperature and RVP fuel volatility,
MPD_j = Miles-per-day values for age *j* vehicles,
CC = Crankcase emissions in grams per mile,
TAMPCC = Excess crankcase emissions due to tampering.

Running loss emissions (RNGLOS) are calculated in a similar manner: loss emission rates in grams per mile are corrected for temperature and RVP fuel volatility (RULOSS), and then are added to the excess running loss emissions ascribed to tampering (TAMPRL).

Refueling loss emissions (REFUEL) are calculated by adding together the displacement fueling losses corrected for RVP fuel volatility (DISP) and an average spillage rate (SPILL), both measured in grams per gallon. This figure is divided by the road fuel economy rate (ROADFE), measured in gallons per mile.

All evaporative emission factor components are modeled as a function of the ambient temperature

and fuel volatility. Running losses are modeled with two additional variables — average speed and trip duration. Refueling losses are modeled with one additional variable, defined as the temperature difference between the dispensed fuel and the residual tank fuel. EPA has also recently incorporated into its modeling the results of inspection/maintenance program testing for fuel/evaporative control system leaks and the capability of the carbon canister to properly purge vapors. The impact of "pressure and purge" problems on hot soak, diurnal, and running loss emission rates are reflected in MOBILE4.1.[55]

Calculation of Travel Weighting Fractions. After emission factor corrections have been applied to the basic exhaust emission factors, and hydrocarbon evaporative and exhaust emission factor components have been added together, travel weighting fractions (TFs) are applied for deriving the final consolidated emission factors.

The TFs represent model-year proportions of total vehicle-miles-traveled for each vehicle type. They are calculated with the use of an annual mileage accumulation rate distribution, a registration distribution[56], and a diesel sales distribution (applicable to all vehicle types *except* heavy-duty gas-powered vehicles and heavy-duty gas-powered trucks).

Example 2 shows the calculation of a consolidated hydrocarbon emission factor for model-year 1988 light-duty gasoline-powered vehicles.

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[55] User's Guide to MOBILE4.1, Sec. 1.1.6, p. 1-12.

[56] The EPA collects July 1 registration data, which is adjusted to reflect registration activity as of January 1. Vehicle sales are assumed to be uniform throughout the year.

Example 2: Calculating a Consolidated Hydrocarbon Emission Factor for Light-Duty Gasoline Powered Vehicles

Assumptions:

(1) HC emissions are for light-duty gasoline-powered vehicles with a 1988 evaluation calendar year, 20-model-year vehicle window, with testing conducted at low altitude.
(2) Daily minimum and maximum ambient temperatures are 60°F and 80°F, respectively.
(3) All conditions match the basic federal test conditions (i.e., air conditioning, extra load, trailer towing, humidity levels, and other basic exhaust emission correction factors have no affect on the calculations, and are therefore set to 1.0).
(4) No inspection/maintenance or anti-tampering programs are assumed.
(5) Certification fuel volatility of 9.0 psi is assumed.
(6) Total HC emissions are calculated at an average speed of 30 miles per hour.
(7) Percentages of vehicle-miles-traveled in the cold start, stabilized, and hot start operating modes are 40%, 30%, and 30%, respectively.
(8) Basic HC emission factors are adjusted for the effects of tampering.
(9) Methane is included in HC calculations.

Consolidated Emission Factor Equation

$$CONBEFHC_n = \sum TF_i * [(BEF * SALHCF) + REFUEL + RNGLOS + CCEVERT]$$

where:

$CONBEFHC_n$= Consolidated Hydrocarbon Emission Factor for calendar year *n*,
TF_i= Travel Weighting Fraction for Model Year *i*,
BEF= Adjusted Hydrocarbon Exhaust Emission Factor,
SALHCF= Speed Correction Factor,
REFUEL= Refueling HC Emission Factor,
RNGLOS= Running Loss HC Emission Factor,
CCEVERT= Crankcase and Evaporative HC Emission Factor.

Data Table

Model Year (i)	TF	BEF (gpm)	SALHCF (gpm)	REFUEL (gpm)	RNGLOS (gpm)	CCEVERT (gpm)	$CONBEFHC_n$: TF*(BEF*SALHCF)+ REFUEL+RNGLOS+ CCEVERT
1988*	0.0307	0.415	0.730	0.243	0.254	0.147	0.029
1987	0.1209	0.472	0.730	0.244	0.254	0.155	0.121
1986	0.1102	0.577	0.730	0.248	0.264	0.177	0.122
1985	0.0985	0.688	0.730	0.255	0.275	0.215	0.123
1984	0.0879	0.808	0.730	0.262	0.285	0.258	0.123
1983	0.0783	0.938	0.730	0.266	0.294	0.300	0.121
1982	0.0679	1.257	0.730	0.263	0.303	0.345	0.124
1981	0.0598	1.480	0.730	0.272	0.311	0.390	0.123
1980	0.0537	2.507	0.730	0.291	0.551	0.576	0.174
1979	0.0481	4.941	0.730	0.335	0.559	0.620	0.246
1978	0.0427	5.253	0.730	0.339	0.566	0.665	0.231
1977	0.0381	5.505	0.730	0.370	0.650	1.515	0.250
1976	0.0328	5.807	0.717	0.387	0.656	1.593	0.223
1975	0.0280	6.043	0.717	0.427	0.662	1.674	0.199
1974	0.0237	5.844	0.706	0.473	0.668	1.759	0.167
1973	0.0197	5.945	0.706	0.473	0.673	1.846	0.142
1972	0.0167	5.906	0.795	0.465	0.679	1.937	0.130
1971	0.0134	9.089	0.798	0.469	0.683	2.726	0.149
1970	0.0104	9.296	0.811	0.451	0.715	3.556	0.128
1969	0.0185	8.856	0.781	0.454	0.684	3.660	0.217
$\sum_{i=a-11}^{a}$							= 3.142

Data Source: U.S. Environmental Protection Agency Office of Mobile Sources, *Supplement A. Compilation of Air Pollutant Emission Factors, Volume II - Mobile Sources* (AP-42), January 1991, Appendix G.

DAC Highway Mobile Source Emissions Factor Methodology

Carbon Monoxide, Volatile Organic Compound, and Nitrogen Oxide Emission Factors: Conventional Vehicles

DAC calculated VOC, CO, and NO_x emission factors for highway sources using a two-step methodology. First, MOBILE4.1 model runs were conducted to obtain baseline emission factor forecasts. Second, off-line adjustments to the baseline emission factor forecasts were made to reflect the new CAAA regulations that have not been incorporated into the MOBILE4.1 solution algorithms. Table F-35 provides the adjusted MOBILE4.1 emission factors for conventional vehicle types.[57] The vehicle types consist of LDGVs, LDGTs (combined Class 1 and 2), HDGVs, LDDVs, LDDTs, and HDDVs. Table F-36 provides the EPA definitions for each of the vehicle-type categories.

Emission factors for heavy-duty diesel-powered vehicles (HDDVs) should be used for diesel-powered buses. This is recommended by the EPA, which cites the similarities between the two vehicles types as well as the lack of comprehensive emission testing for buses (note that the EPA bus emission factors are reported in grams per mile as opposed to the TERF lbs./1,000 gal. specification). Efforts at improving the EPA bus emission data base are ongoing because of concern that the HDDV emission factors do not accurately reflect in-use characteristics of buses in urban areas.

A complication results in trying to combine the EPA vehicle-type emission factors into the freight truck category designated in the TSCDR. As shown in Table F-36, the EPA vehicle-type categories for heavy-duty vehicles and trucks do not correspond to the weight categories used by either the TIUS or the FHWA Highway statistics report. The EPA uses a weight cut-off of 8,500 pounds GVW for its heavy-duty classifications. Trucks with an average weight greater than 10,000 pounds are classified as medium, light-heavy, or heavy-heavy by the TIUS. There is no weighting method that proves satisfactory for normalizing the EPA emission factors to the FHWA weight categories. Therefore, we recommend that the EPA emission factors for gasoline and diesel heavy-duty vehicles (HDGVs and HDDVs) be used as the TERF freight truck emission factors.

[57] Five-year interval forecasts were interpolated to produce year-to-year emission factors.

Table F-35. Adjusted MOBILE4.1 Emission Factors

YEAR	LDGV			LDGT			HDGV		
	VOC	CO	NOx	VOC	CO	NOx	VOC	CO	NOx
1990	2.09	20.63	1.43	4.20	29.16	1.93	10.84	101.36	5.82
1991	2.33	18.67	1.16	3.84	26.16	1.81	9.90	90.91	5.61
1992	2.59	16.89	0.94	3.51	23.47	1.70	9.05	81.53	5.41
1993	2.89	15.28	0.76	3.21	21.06	1.59	8.27	73.12	5.21
1994	3.22	13.83	0.62	2.93	18.89	1.49	7.55	65.58	5.02
1995	3.59	12.51	0.50	2.68	16.95	1.40	6.90	58.82	4.84
1996	2.98	11.88	0.50	2.54	15.72	1.35	6.45	52.74	4.73
1997	2.47	11.29	0.50	2.41	14.58	1.29	6.04	47.28	4.63
1998	2.05	10.72	0.50	2.28	13.53	1.24	5.65	42.39	4.53
1999	1.70	10.18	0.50	2.16	12.55	1.20	5.28	38.01	4.43
2000	1.41	9.67	0.50	2.05	11.64	1.15	4.94	34.08	4.33
2001	1.34	9.27	0.50	1.96	11.01	1.13	4.66	31.50	4.29
2002	1.27	8.88	0.50	1.87	10.41	1.10	4.40	29.11	4.26
2003	1.21	8.51	0.50	1.79	9.85	1.08	4.15	26.90	4.22
2004	1.15	8.15	0.50	1.71	9.31	1.06	3.92	24.86	4.19
2005	1.09	7.81	0.50	1.63	8.81	1.04	3.70	22.98	4.15
2006	1.09	7.78	0.50	1.62	8.75	1.04	3.66	22.33	4.13
2007	1.09	7.76	0.50	1.62	8.69	1.03	3.61	21.71	4.11
2008	1.08	7.73	0.50	1.61	8.63	1.03	3.57	21.10	4.10
2009	1.08	7.71	0.50	1.61	8.58	1.02	3.53	20.51	4.08
2010	1.08	7.68	0.50	1.60	8.52	1.02	3.49	19.93	4.06
2011	1.08	7.67	0.50	1.60	8.52	1.02	3.49	19.87	4.05
2012	1.08	7.67	0.50	1.60	8.52	1.02	3.49	19.81	4.04
2013	1.08	7.66	0.50	1.60	8.52	1.01	3.48	19.76	4.04
2014	1.08	7.66	0.50	1.60	8.52	1.01	3.48	19.70	4.03
2015	1.08	7.65	0.50	1.60	8.52	1.01	3.48	19.64	4.02
2016	1.08	7.65	0.50	1.60	8.52	1.01	3.48	19.64	4.02
2017	1.08	7.65	0.50	1.60	8.51	1.01	3.48	19.64	4.02
2018	1.08	7.65	0.50	1.60	8.51	1.01	3.48	19.63	4.02
2019	1.08	7.65	0.50	1.60	8.50	1.01	3.48	19.63	4.02
2020	1.08	7.65	0.50	1.60	8.50	1.01	3.48	19.63	4.02
2025	1.08	7.65	0.50	1.60	8.50	1.01	3.48	19.63	4.02
2030	1.08	7.65	0.50	1.60	8.50	1.01	3.48	19.63	4.02

Adjustment notation:

(1) LDGV's: Adjust VOC downward by 0.14 gpm for 1995 through 2030 to reflect decrease in exhause emission standard from 0.39 gpm to 0.25 gpm.

(2) LDGV'S: Assume NO_x emissions of 0.50 gpm beginning in 1995 and forward to reflect new/in-use standard fo 0.40 gpm and 0.6 gpm 100,000-mile certification standard.

(3) LDGV's: CO emission factors include new cold temperature standards.

(4) LDDV's: MOBILE4.1 emission factors are below standards; therefore no adjustments to LDDV emission factors are necessary.

(5) HDDV's: MOBILE4.1 incorporates 1994 HC and CO standards. NO_x standard was lowered, but MOBILE4.1 produces forcast emission factors at about the same level as the standards.

Table F-35. (Continued)

YEAR	LDDV			LDDT			HDDV		
	VOC	CO	NOx	VOC	CO	NOx	VOC	CO	NOx
1990	0.71	1.67	1.63	0.96	1.90	1.87	2.84	13.03	19.45
1991	0.72	1.68	1.63	0.97	1.91	1.86	2.73	12.75	17.72
1992	0.73	1.70	1.64	0.98	1.91	1.85	2.62	12.49	16.14
1993	0.74	1.71	1.64	1.00	1.92	1.85	2.52	12.22	14.70
1994	0.75	1.73	1.65	1.01	1.92	1.84	2.42	11.96	13.39
1995	0.76	1.74	1.65	1.02	1.93	1.83	2.32	11.71	12.20
1996	0.74	1.71	1.59	0.98	1.89	1.76	2.28	11.61	11.56
1997	0.71	1.68	1.53	0.94	1.85	1.69	2.25	11.51	10.94
1998	0.69	1.65	1.48	0.91	1.81	1.62	2.22	11.41	10.37
1999	0.67	1.63	1.42	0.87	1.78	1.56	2.18	11.31	9.82
2000	0.65	1.60	1.37	0.84	1.74	1.50	2.15	11.21	9.30
2001	0.62	1.57	1.32	0.80	1.70	1.44	2.14	11.18	9.11
2002	0.59	1.53	1.27	0.76	1.66	1.39	2.13	11.16	8.92
2003	0.57	1.50	1.22	0.73	1.62	1.33	2.13	11.13	8.73
2004	0.54	1.47	1.17	0.69	1.59	1.28	2.12	11.11	8.55
2005	0.52	1.44	1.13	0.66	1.55	1.23	2.11	11.08	8.37
2006	0.52	1.44	1.12	0.66	1.55	1.22	2.11	11.07	8.32
2007	0.51	1.43	1.11	0.66	1.55	1.21	2.11	11.07	8.27
2008	0.51	1.43	1.09	0.65	1.54	1.21	2.10	11.06	8.21
2009	0.50	1.42	1.08	0.65	1.54	1.20	2.10	11.06	8.16
2010	0.50	1.42	1.07	0.65	1.54	1.19	2.10	11.05	8.11
2011	0.50	1.42	1.07	0.65	1.54	1.19	2.10	11.05	8.10
2012	0.51	1.43	1.08	0.65	1.54	1.19	2.10	11.05	8.09
2013	0.51	1.43	1.08	0.66	1.54	1.19	2.10	11.04	8.07
2014	0.52	1.44	1.09	0.66	1.54	1.19	2.10	11.04	8.06
2015	0.52	1.44	1.09	0.66	1.54	1.19	2.10	11.04	8.05
2016	0.52	1.44	1.09	0.66	1.54	1.19	2.10	11.04	8.05
2017	0.52	1.44	1.09	0.67	1.55	1.20	2.10	11.04	8.05
2018	0.52	1.44	1.09	0.67	1.55	1.20	2.10	11.04	8.05
2019	0.52	1.44	1.09	0.68	1.56	1.21	2.10	11.04	8.05
2020	0.52	1.44	1.09	0.68	1.56	1.21	2.10	11.04	8.05
2025	0.52	1.44	1.09	0.68	1.56	1.21	2.10	11.04	8.05
2030	0.52	1.44	1.09	0.68	1.56	1.21	2.10	11.04	8.05

Adjustment notation:

(1) LDGV's: Adjust VOC downward by 0.14 gpm for 1995 through 2030 to reflect decrease in exhause emission standard from 0.39 gpm to 0.25 gpm.

(2) LDGV'S: Assume NO_x emissions of 0.50 gpm beginning in 1995 and forward to reflect new/in-use standard fo 0.40 gpm and 0.6 gpm 100,000-mile certification standard.

(3) LDGV's: CO emission factors include new cold temperature standards.

(4) LDDV's: MOBILE4.1 emission factors are below standards; therefore no adjustments to LDDV emission factors are necessary.

(5) HDDV's: MOBILE4.1 incorporates 1994 HC and CO standards. NO_x standard was lowered, but MOBILE4.1 produces forcast emission factors at about the same level as the standards.

Table F-36. EPA Highway Vehicle Classification Categories and Definitions

Vehicle-Type Classification Category	EPA Category Definition
Light-duty gasoline-powered vehicles (LDGVs)	Gas-fueled vehicle primarily designed for passenger transportation with a design capacity of 12 persons or less.
Light-duty gasoline-powered trucks, Class 1 (LDGT1s)	Diesel-fueled vehicle primarily designed for passenger transportation with a design capacity of 12 persons or less.
Light-duty gasoline-powered trucks, Class 2 (LDGT2s)	Gas-fueled vehicle with a Gross Vehicle Weight (GVW) between 6,001 and 8,500 pounds.
Heavy-duty gasoline-powered vehicles (HDGVs)	Gas-fueled vehicle designed to carry property, with a Gross Vehicle Weight (GVW) over 8,500 pounds, or; any vehicle designated for passenger transportation having a design capacity of more than 12 persons.
Light-duty diesel-powered vehicles (LDDVs)	Any diesel-fueled vehicle designated primarily for passenger transportation and having a design capacity of 12 persons or less.
Light-duty diesel-powered trucks (LDDTs)	Any diesel-fueled vehicle designed primarily for property transportation, and rated at 8,500 lbs. GVW or less.
Heavy-duty diesel-powered vehicles (HDDVs)	Any diesel-fueled vehicle designed primarily for property transportation, and rated at more than 8,500 lbs. GVW.

Source: U.S. Environmental Protection Agency, *Supplement A to AP-42 Volume II*, January 1991.

DAC obtained the MOBILE4.1 model from the EPA, and used the model to calculate national CO, NO_x, and VOC emission factors to the year 2020 (the last MOBILE4.1 forecast year) using a scenario-based input data set. EPA staff make the assumption that emission factors remain relatively stable after 2010.[58] Therefore, emission factors for 2020 are used for the subsequent forecast years. As already noted, the MOBILE4.1 emission factors do not reflect many new CAAA standards that should affect emission rates after 1993. Post hoc adjustments need to be made to account for new vehicle standards, in-use standards, and other CAAA emission control requirements if the forecasted emission factors exceed the standards in any year. It is important to note that any emission factor adjustments are based on gross assumptions, with the resulting emission factors considered to be interim in nature.

The MOBILE4.1 input data set consists of a series of user-specified control flags, data inputs common to all emission scenarios, and data inputs specific to an individual scenario. In addition to regulating program execution and input/output stream formatting, the control flags determine model actions such as the use of emission control device tampering rates, average vehicle speed selection, mileage accumulation rate selection, VMT mix selection, I/M program impact, ambient temperature selection, and many other factors. Control flags specifying EPA default values and

[58] Personal communication with Lois Platte, EPA Motor Vehicle Emission Laboratory, Ann Arbor, Michigan, June 26, 1992.

national averages were included to the maximum extent.

The greatest difficulty in developing the MOBILE4.1 data set was accounting for the impact of inspection/maintenance programs. MOBILE4.1 was not designed with the capability for estimating national average I/M program impacts. The I/M program data set record must be specified according to local I/M program attributes. Such program attributes are highly customized to met locale-specific implementation needs, and therefore cannot be formulated into a national average I/M program. Further complications result from the fact that I/M programs are not required nor implemented in many areas of the country, and new EPA regulations have resulted in greater complexity for existing and planned programs.

To account for the effects of I/M and anti-tampering programs on emission factors, a model-run interpolation method was used. Inspection and maintenance programs are required for 162 ozone areas based on CAAA regulations. A data set was created that included parameters and data for an "enhanced" I/M model program (required for serious, severe, and extreme ozone nonattainment areas) as outlined in the EPA's Notice of Proposed Rulemaking.[59] An enhanced I/M program includes annual centralized testing for light-duty vehicles and trucks, and include such tests as the transient IM240 exhaust emission test, the transient purge test, the pressure test, the two-speed exhaust test, and the idle exhaust test. The EPA estimates that such an I/M program could reduce vehicle VOC emissions by 28 percent, CO emissions by 30 percent, and NO_x emissions by 9 percent.[60]

A MOBILE4.1 emission factor based on national imposition of enhanced I/M programs is assumed to represent an upper bound for vehicle emissions. To account for areas that have no I/M and anti-tampering programs, a MOBILE4.1 data set was created that excluded operating I/M and anti-tampering programs. Separate sets of emission factors were generated from MOBILE4.1 model runs employing each data set. Composite emission factors were derived by taking the arithmetic average of the two emission factor sets. Ideally, the composite emission factor set should be calculated as a weighted average, using vehicle mileage data for each type of ozone nonattainment area and I/M program type. Such a procedure is complex and time-consuming (and perhaps not doable because of the flexibility afforded to the states for choosing I/M program elements), and could not be attempted given the resources available for this subtask. The simple arithmetic average approach, while producing somewhat arbitrary results, is superior to assuming

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[59] EPA Notice of Proposed Rulemaking, "Vehicle Inspection and Maintenance Requirements for State Implementation Plans," 40 CFR Part 51, July 9, 1992.

[60] Ibid., section II.

a universally-applied I/M program for all areas of the country. Such an assumption yields overly-optimistic emission factor reductions.

Sulfur Dioxide and Carbon Dioxide Emission Factors: Conventional Vehicles

The EPA does not regularly monitor and report carbon dioxide and sulfur dioxide emissions for highway mobile sources. The relatively small amounts of SO_2 emitted by trucks and cars are quickly converted to sulfuric acid, and therefore do not represent a significant air pollution hazard. Although the EPA produced SO_2 measurement procedures in the early 1980's, the Agency has not published SO_2 emission factors.[61]

The SO_2 and CO_2 emission factors to be used in TERF come from the Argonne National Laboratory's Transportation Energy and Emissions model (TEEMS). Table F-37 provides the emission factors produced for the DOE Office of Environmental Analysis as part of data input to the NESEAM model.[62] These emission factors include the effects of CAAA emission standards, and are forecasted to the year 2030.

The TEEMS/NEASAM emission factors were reported in pounds of emissions per million Btu. To convert the emission factors to a grams-per-mile equivalent, the following formula was used:

$$EF_{gpm} = EF_{ppBtu} \times 57.9549 / MPG_c$$

where:

EF_{gpm} = Emission factor in grams per mile,
EF_{ppBtu} = TEEMS emission factor in pounds per million Btu,
MPG = TEEMS forecasted fuel economy for category c vehicles in gallons per mile,

The TEEMS model does not report CO_2 emission factors for heavy-duty diesel trucks and heavy-duty gasoline vehicles.

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[61] Personal communication with Penny Carey, EPA Motor Vehicle Emissions Laboratory, Ann Arbor, Michigan, August 4, 1992.

[62] See, *Decision Analysis Corporation, Mobile Source Air Emissions Regulations and Inventories, Draft Report*, (Prepared for the EIA Energy Demand Analysis Branch under Contract No. DE-AC01-92EI21946, July 15, 1992).

Table F-37. LDV Sulfur Dioxide and Carbon Dioxide Emission Factors (Grams/Mile)

YEAR	SO2					CO2		
	HDDT	HDGV	LDDT	LDGT	LDGV	LDDT	LDGT	LDGV
1990	1.3892	0.3890	0.5156	0.0968	0.0846	178.2613	178.2613	98.0075
1991	1.0592	0.3913	0.3898	0.0957	0.0827	176.1273	176.1273	96.8204
1992	0.8075	0.3937	0.2947	0.0947	0.0809	174.0188	174.0188	95.6477
1993	0.6157	0.3961	0.2228	0.0937	0.0791	171.9355	171.9355	94.4891
1994	0.4694	0.3985	0.1685	0.0927	0.0773	169.8771	169.8771	93.3446
1995	0.3579	0.4009	0.1274	0.0917	0.0756	167.8435	167.8435	92.2140
1996	0.3586	0.3987	0.1263	0.0913	0.0747	167.1971	167.1971	91.5909
1997	0.3593	0.3966	0.1253	0.0910	0.0738	166.5531	166.5531	90.9719
1998	0.3600	0.3945	0.1243	0.0906	0.0729	165.9117	165.9117	90.3572
1999	0.3607	0.3924	0.1233	0.0902	0.0721	165.2728	165.2728	89.7466
2000	0.3615	0.3904	0.1222	0.0898	0.0712	164.6363	164.6363	89.1402
2001	0.3540	0.3895	0.1206	0.0887	0.0705	162.6740	162.6740	87.8486
2002	0.3467	0.3886	0.1190	0.0875	0.0698	160.7351	160.7351	86.5757
2003	0.3396	0.3877	0.1174	0.0863	0.0691	158.8193	158.8193	85.3213
2004	0.3326	0.3869	0.1158	0.0852	0.0684	156.9264	156.9264	84.0850
2005	0.3258	0.3860	0.1143	0.0841	0.0678	155.0560	155.0560	82.8667
2006	0.3191	0.3851	0.1127	0.0830	0.0671	153.2080	153.2080	81.6660
2007	0.3125	0.3843	0.1112	0.0819	0.0664	151.3819	151.3819	80.4827
2008	0.3061	0.3834	0.1097	0.0808	0.0658	149.5776	149.5776	79.3166
2009	0.2998	0.3825	0.1082	0.0797	0.0651	147.7948	147.7948	78.1673
2010	0.2936	0.3817	0.1068	0.0787	0.0645	146.0333	146.0333	77.0347
2020	0.31806	0.413476	0.10608	0.076857	0.063419	146.0333	146.0333	77.03472
2030	0.31806	0.413476	0.10608	0.076857	0.063419	146.0333	146.0333	77.03472

Source: Argonne National Laboratory Transportation Energy and Emissions Modeling System (TEEMS), Model run ANL-90N.

Total Carbon Emission Factors: Conventional Vehicles

The calculation of total carbon emission factors for gasoline and diesel fuels is straightforward. The following formulae are used to produce carbon emission factors in grams per mile:

$$CarbonEF_{gas} = 0.866 * (2791.0/MPG)$$
$$CarbonEF_{diesel} = 0.858 * (3192.0/MPG)$$

The constant values of 0.886 and 0.858 are the carbon mass fractions of gasoline and diesel, respectively.[63] The constant values of 2791 and 3192 are the densities for gasoline and diesel fuel, and were obtained from EIA's *1989 International Energy Annual* (February 1991).[64] To obtain the carbon emission factors, the endogenously calculated TERF miles-per-gallon estimates (MPG) will need to be passed to the emissions module. As currently configured, MPG forecasts will be determined using the Argonne National Laboratory TEEMS methodology, which uses lagged MPG and other economic variables.

Using Argonne's ANL-90N TEEMS run as an example, automobile and diesel freight truck carbon emission factors for 1990, 1995, 2005 and 2010 are shown below (MPG figures are in parentheses).

Year	Emission Factor, g/mile (MPG)	
	Automobiles	Light Trucks
1990	120.8 (20.0)	464.2 (5.9)
1995	119.5 (20.7)	449.0 (6.1)
2000	116.1 (21.3)	427.9 (6.4)
2005	107.5 (23.0)	421.3 (6.5)
2010	89.3 (27.7)	415.0 (6.6)

[63] This value is reported by the EPA. See, Frank Black, 3rd U.S. - Dutch International Symposium, "Atmospheric Ozone Research and Its Policy Implications" (May 9-13, 1988, Nijmegen, the Netherlands), or the DeLuchi/Argonne greenhouse gas study.

[64] Appendix F, Volume, Weight, and Monetary Conversions, p. 149.

Emission Factors: Alternative Fuel Vehicles

The calculation of emission factors for alternative fuel vehicles (AFVs) is subjective in nature, and depends on emissions data from test vehicles and the likely capability of AFVs to meet new CAAA clean-fuel vehicle emission standards. Emission factors for NMHC, CO, NO_x, and CO_2 were provided to Argonne National Laboratory in a greenhouse gas emission study conducted jointly by the Institute of Transportation Studies at the University of California-Davis, and the Center for Energy and Environmental Studies at Princeton University.[65] Table F-38 lists these AFV emission factors for light-duty vehicles (LDV's) and heavy-duty vehicles, such as freight trucks and buses (HDV's), powered by the following fuels: methanol (100%), compressed natural gas, hydrogen, ethanol (100%), and liquid petroleum gas (LPG). Electric vehicles are considered to emit no pollutants other than a small quantity of chlorofluorocarbons (CFCs).

Table F-38. Lifetime Average Emission Factors for Alternative Fuel Vehicles (Grams per Mile)

	Methanol*		Natural Gas		Hydrogen		Ethanol*		LPG	
	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV	LDV	HDV
NMHC	0.56	4.86	0.22	0.60	0.04	0.04	0.38	4.42	0.22	1.80
CO	7.21	13.00	3.60	7.00	0.70	0.10	7.21	13.00	5.50	9.00
NO_x	0.45	8.05	0.45	8.05	0.45	8.05	0.45	8.05	0.45	8.05
CO_2	214.64	1495.41	195.51	1463.94	0.00	0.00	0.00	0.00	226.72	1695.56

*Emission factors are for M100 (100% methanol) and 100% ethanol fuels.

[65] Mark A. DeLuchi, University of California Institute of Transportation Studies, *Emissions of Greenhouse Gases From the Use of Transportation Fuels and Electricity* (for the Argonne National Laboratory Center for Transportation Research, June 26, 1991).

OFF-HIGHWAY SOURCES EMISSIONS FACTORS

Off-Highway Mobile Source Emission Factor Information Sources

The following documents were used to compile off-highway emission factors or supply background information on emission factor calculation methods:

- *Compilation of Air Pollutant Emission Factors - Volume II: Mobile Sources* (AP-42, Fourth Edition, September 1985)

- *Nonroad Engine and Vehicle Emission Study—Report*, EPA 460/3-91-02 (November 1991)

- *Interim Guidance for the Preparation of Mobile Source Emission Inventories*, Attachments A through J (This EPA memorandum supersedes the mobile source emission inventory preparation instructions contained in *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, which is currently being revised)

- *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, EPA-450/4-81-026d (revised), (July 1992).

The document, *Compilation of Air Pollutant Emission Factors - Volume II*, reports all data and emission factor calculation algorithms for both highway and off-highway emission sources. Section II outlines the emission calculation methodologies for off-highway mobile sources, including aircraft, railroad locomotives, inboard-powered vessels, outboard-powered vessels, small general utility engines, agricultural equipment, heavy duty construction equipment, and snowmobiles. The EPA is planning to issue an updated version of the AP-42 document, although no estimate has been given as to the release date. The EPA's *Nonroad Engine and Vehicle Emission Study*, which was mandated as part of CAAA Section 213(a), provides new or updated emission inventory data and emission factors for ten nonroad equipment categories including commercial marine vessels, which is one of the transport modes to be modeled in TERF.[66] The

[66] The other nine equipment categories are lawn and garden equipment, airport service equipment, recreational vehicles, recreational marine equipment, light commercial equipment, industrial equipment, construction equipment, agricultural equipment, and logging equipment.

Nonroad Emission study targeted 24 nonattainment areas as well as national totals. The document, *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*, provides state and local agencies with detailed guidance on the preparation of highway and off-highway mobile source emission inventories. The off-highway emission factors contained in this section were derived either directly from the inventory preparation procedure report, or were calculated using data tables contained therein.

Railroad Locomotive Emission Factors

Table F-39 lists the railroad locomotive emission factors to be incorporated into the TERF model. Emission factors for CO, NO_x, SO_2 and HC are included.[67] Note that the EPA does not measure separately the volatile component of total hydrocarbons. Also, no distinction is made between freight and passenger locomotives because both travel modes use the same locomotive technology types. These emission factors are reported in the July 1992 edition of *Procedures for Emission Inventory Preparation — Volume IV, Mobile Sources*. They are considered default values for fleet-average line haul locomotives.[68] Line haul locomotives represent the largest segment of the locomotive population, and include all locomotives used for freight and passenger service. As of mid-1991, 9,708 line haul locomotives were in service.[69] Yard locomotives are used for moving railcars within a rail switchyard, and are considered a negligible source of emissions. As of mid-1991, 4,589 yard locomotives were in service.[70]

The emission factors represent an average of emission factors for five diesel engine configuration types: 2-stroke supercharged switch locomotive, 4-stroke switch locomotive, 2-stoke supercharged road service locomotive, 2-stroke turbocharged road service locomotive, and 4-stroke road service locomotive. The emission factors are based on duty cycle testing and average fuel consumption rates. A duty cycle consists of the operating time in eight throttle notch settings plus idle and dynamic braking. The fuel consumption rate of a locomotive is determined by the throttle notch position — the higher the notch, the higher the fuel consumption, and vice versa.

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[67] Source: EPA Office of Mobile Sources, *Locomotive Emission Factors for Inventory Guidance Document* (June 1991).

[68] The EPA also outlines a methodology for calculating more detailed locomotive emissions for areas that are expected to deviate significantly from the national average. The methodology is called the *roster tailoring method*, and uses emissions data from individual locomotive makes and models.

[69] *Interim Guidance for the Preparation of Mobile Source Emission Inventories*, Attachment J, Emissions from Railroads (EPA Office of Mobile Sources, February 15, 1992), Appendix 6-5, p. 6-23.

[70] Ibid, p. 6-23.

Therefore, fuel consumption is proportional to the amount of time the locomotive spends in each throttle notch position.[71] The locomotive emission factors apply to all three Interstate Commerce Commission (ICC) railroad classes: Class I — annual revenues greater than $93.5 million; Class II — annual revenues greater than $18.7 million but less than $93.5 million; Class III — annual revenues less than $18.7 million.

Table F-39. TRAN Locomotive Emission Factors

Pollutant	Emission Factor (lbs./1,000 gal of fuel)
HC	21.10
CO	6.26
NO_x	493.10
SO_2*	36.00
PM	11.60

*Based on fuel sulfur content of 0.25 percent by weight.

Look-Ahead Issues Concerning Locomotive Emission Factors

In terms of specifying future-year locomotive emission factors given CAAA requirements, the emission factors in Table F-39 are to be used for all forecast years. Section 213 of the Amended Act requires the EPA to promulgate emission standards for new locomotives by November 1995. These new standards are to be designed to obtain the greatest degree of emission reduction achievable, with due consideration given to compliance cost, energy consumption, safety and noise.[72] New emission factors would be based on testing of the applicable locomotive emission reduction technologies that would be manufactured to comply with new standards. Given the large uncertainty over the prospective emission standards and technologies, as well as the low stock turnover of locomotive engines, there is no justification for assigning alternative emission factors to the forecast interval.

[71] Ibid, p. 6-13.

[72] CAAA, sec. 213 (a)(5), 104 STAT 2501.

Aircraft Emission Factors

Overview of the EPA Aircraft Emissions Inventory Methodology

The EPA bases its aircraft emission factors on five operating modes that together consist of the landing and takeoff (LTO) cycle. The first operating mode is the approach, in which the aircraft makes its airport approach after the descent from cruising altitude. The second operating mode is taxi/idle-in, where the aircraft lands and taxis to the gate. The third mode is taxi/idle-out, in which the aircraft taxis back out to the runway for subsequent takeoff.[73] The fourth mode is takeoff, in which the aircraft attains liftoff speed and becomes airborne. The fifth mode is termed the climbout, and represents the aircraft's accent to cruising altitude. Most aircraft go through a similar sequence during an LTO cycle.

During each operation mode the aircraft engines operate at a fairly standard power setting for a given aircraft category. The power setting results in a certain rate of fuel flow (expressed in pounds per minute) for the operating mode. Total emissions from the aircraft engine are thus determined by the amount of time that an aircraft engine spends in each operation mode (termed the "Time-in Mode"), the fuel consumption rate, and the engine-specific emission factors for each operating mode, expressed in pounds of emissions per 1,000 pounds of fuel consumed.

The EPA aircraft emission factors and inventory preparation procedures are site-specific; they are highly dependent on local airport and aircraft population data. Generally, the emissions inventory is prepared using the following steps: (1) identify airports to be included in the inventory area, (2) determine the mixing height[74] to be applied to the LTO cycle (a standard default value of 3,000 feet is assumed), (3) define the aircraft fleet population for each aircraft category across all airports, (4) determine the number of LTOs for each aircraft category, (5) select emission factors for each aircraft category, (6) estimate a time-in-mode for each aircraft category at each airport, and (7) calculate an inventory based on the airport activity, time-in-mode, and emission factors.

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[73] Both Taxi/idle operating modes are highly variable, and depend on such factors as airport size and layout, the amount of ground congestion, airport-specific operational procedures, time of day, and seasonal travel activity.

[74] The height of the mixing zone — that portion of the atmosphere where aircraft emissions affect ground level pollutant concentrations — influences the time-in-mode for approach and climbout operation modes, and is particularly significant when calculating NO_x emissions.

EPA Aircraft Categorization

The EPA categorizes aircraft by the type of use: commercial, general aviation, and military. Commercial aircraft include those used for scheduled service transporting passengers, freight, or both. Air taxis also fly scheduled service carrying passengers and/or freight, but usually are smaller aircraft and operate on a more limited basis than the commercial carriers. Business aircraft support business travel, usually on an unscheduled basis, and general aviation includes most other non-military aircraft used for recreational flying, personal transportation, and various other activities.

The EPA combines business aircraft with general aviation aircraft because of their similar size, use frequency, and operating profiles. Similarly, air taxis are treated much like the general aviation category because they are typically the same types of aircraft. Military aircraft cover a wide range of sizes, uses, and operating missions. While they often are similar to civil aircraft, they are handled separately because they typically operate exclusively out of military air bases and frequently have distinctive flight profiles. Helicopters, or rotary wing aircraft, can be found in each of the categories. Their operation is distinct because they do not always operate from an airport but may land and takeoff from a heliport at a hospital, police station, or similarly dispersed location. Military rotorcraft are included in the military category and non-military rotorcraft are included in the general aviation category since information on size and number are usually found in common sources. However, they are combined into a single group for calculating emissions since their flight profiles are similar.

Commercial aircraft typically are the largest source of aircraft emissions. Although they make up less than half of all aircraft in operation around a metropolitan area, their emissions usually represent a large fraction of the total because of their size and operating frequency. This would not hold true for a city with a disproportionate amount of military activity, or a city with no major civil airports.

Aircraft Emissions Characteristics

The EPA views HC, CO, NO_x, SO_2, and PM_{10} as the significant aircraft pollutants. However, only HC emissions and smoke production are currently regulated.[75] For a single LTO cycle,

[75] EPA established standards for aircraft HC emissions in 1984, which included the establishment of standard procedures for engine certification and emissions testing. The standard applies to jet engines with an engine thrust of over 6,000 pounds. The EPA reports that many older in-service engines exceed the standards. New engine designs produced since the standards went

aircraft emissions vary considerably depending on the category of aircraft and the aircraft's flight profile. Emission rates for HC and CO are high during the taxi/idle phases when aircraft engines are at low power and operate at suboptimum efficiency. The emission rates fall as the aircraft moves into the higher power operating modes of the LTO cycle. Conversely, NO_x emissions are low when engine power and combustion temperature are low, but increase as the power level is increased and combustion temperature rises. Therefore the takeoff and climbout modes have the highest NO_x emission rates.

Sulfur dioxide emission rates are highest during the takeoff and climbout operation modes when fuel consumption rates are high. Sulfur emissions typically are not measured when aircraft engines are tested. Therefore, the EPA uses a default emission factor of 0.54 pounds SO_2 per 1,000 pounds of fuel for all engine types. (EPA assumes that all sulfur in the fuel combines with oxygen during combustion to form SO_2. Nationally, the sulfur content of fuel remains fairly constant from year to year at about 0.05% by weight for commercial jet fuel, 0.025% by weight for military fuel, and 0.006% by weight for aviation gasoline. These national sulfur content figures are used by the EPA for estimating the SO_2 default emission factors.

Particulate emission characteristics are similar to that of HC and CO in that emission rates are higher at low power rates than at high power rates because of greater combustion efficiency at a higher engine power. However, particulate emissions are highest during takeoff and climbout due to the greater fuel flow rate. The EPA does not report emission factors for particulates except for a small number of engine models, citing the difficulty in estimating PM emissions.[76] Direct measurement of particulate emissions from aircraft engines typically are not available from manufacturers, although emission of visible smoke is reported as part of the engine certification procedure.[77] The inventory preparation procedure document reports emission factors for only one civil aircraft engine model. This engine model is used in a number of European-built aircraft, and is not representative of the total aircraft fleet.

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into effect have HC emissions lower than the standards, but the design changes made to reduce the HC emissions resulted in small increases in NO_x emissions.

[76] *Procedures for Emission Inventory Preparation, Vol IV*, page 149.

[77] Ibid., p. 149.

DAC Methodology for Calculating Aircraft Emission Factors

As mentioned above, the EPA aircraft emission factors are reported for individual engine models (currently 88 civil aircraft engines and 54 military engines) by LTO operation mode. Consequently, the emission factors apply to activity levels measured in full LTO cycles, not fuel consumption as specified in the TSCDR. DAC developed a methodology for converting the EPA operating-mode emission factors into a fleet average emission factor based on total gallons of fuel consumed. The data used to construct the fuel-based emission factors are presented in Appendix E.EM.C.

The first step of the conversion methodology involves the derivation of fleet-average time-in-mode figures. The EPA reports default TIM values in minutes for each civil and military aircraft category. Since commercial aircraft accounted for 93.6 percent of civil aircraft energy consumption in 1989, the TIM values for jumbo, long, and medium range jet commercial carriers were used as proxies for the entire civil aircraft population.[78] These TIM figures are as follows: Takeoff — 0.7 minutes, Climbout — 2.2 minutes, Approach — 4.0 minutes, Taxi/Idle — 26.0 minutes. Military aircraft TIM's are highly variable. Therefore, the arithmetic averages of TIMs for combat, trainer, and transport aircraft were used as proxies for the fleet TIMs. Helicopter TIMs were excluded from the calculations due to LTO incompatibility with the other aircraft categories.

The second step of the conversion methodology is to determine the fuel use for each operating mode using the EPA's fuel flow data, and to construct fuel consumption shares. The LTO time-in-mode amounts (in minutes) were multiplied by the fuel flow amounts (in pounds per minute) to obtain fuel consumption in pounds for each operating mode. The modal fuel consumption figures were then divided by total LTO fuel consumption to derive the fuel consumption shares (see Appendix E.EM.C, pages E.EM.C-3 and E.EM.C-6).

The third step is to calculate average emission factors by pollutant type for the population of engine models reported by the EPA. Separate samples of 46 civil and 15 military aircraft engine models were created from the EPA's list.[79] The selection was based on reported engine market shares for each aircraft model, with aircraft models chosen based on a proportional representation

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[78] Aircraft Btu energy consumption figures come from Oak Ridge National Laboratory, *Transportation Energy Data Book, Edition 12*, ORNL-6710 (Oak Ridge, Tennessee, March 1992).

[79] *Procedures for Emission Inventory Preparation*, Table 5-4, "Commercial Aircraft types and Engine Models," and Table 5-6, "Military Aircraft types and Engine Models."

of the commercial, general and military aircraft categories. The sample engine-model emission factors were aggregated by calculating the arithmetic average of reported pollutant emission factors.[80] (see Appendix E.EM.C, pages E.EM.C-1, E.EM.C-2, E.EM.C-4, and E.EM.C-5). Since the SO_2 emission factor is the same for each operation mode, this methodology is not applicable for SO_2 emission rate estimation.

The fourth step is to calculate the weighted fleet-average emission factors for HC, CO, and NO_x by multiplying the aggregated engine sample emission factors by the fuel consumption shares calculated in step 2. Two further calculations are necessary to produce emission factors that correspond to TSCDR specifications. First, the emission factors must be converted into gallons-of-fuel equivalents. A conversion factor of 6.2 pounds per gallon was used. Second, the total HC emission factors must be adjusted to produce volatile organic compound (VOC) emission factors. The following EPA adjustment factors, applicable to turbine engines, were used:

$$VOC_{COMMERCIAL} = THC_{COMMERCIAL} \times 1.0947$$
$$VOC_{MILITARY} = THC_{MILITARY} \times 1.1046$$

Table F-40 presents the TERF aircraft emissions factors for HC, VOC, CO, NO_x, and SO_2.[81]

Table F-40. TERF Aircraft Emission Factors

Pollutant	Emission Factors (lbs./1000 gal. of fuel)	
	Commercial Aircraft	Military Aircraft
HC	37.82	75.54
VOC	41.40	83.44
CO	101.97	330.17
NO_x	79.04	58.15
SO_2	3.35	3.35

[80] Ibid., Table 5-4, "Modal Emission Rates."

[81] Source: Appendix E.EM.C, page E.EM.C-3;

Notes: Commercial and military VOC emission factors calculated by multiplying Appendix E.EM.C HC values by 1.0947 and 1.1046, respectively.

SO_2 emission factors calculated by dividing the EPA standard value of 0.54 pounds per 1,000 gallons by 6.2.

Table F-41. Aircraft Emissions Data

Jet Engine Model-Series	Manufact.	Fuel Flow by Operating Mode (lbs/min)				HC Emissions by Operating Mode (lbs/1,000 lbs)			
		Takeoff	Climbout	Approach	Taxi/Idle	Takeoff	Climbout	Approach	Taxi/Idle
CF6-6D	GE	229.63	189.29	64.01	22.86	0.30	0.30	0.70	21.00
CF6-50E/C1/E1/C2/E2	GE	321.17	254.63	87.86	22.24	0.60	0.70	1.00	49.30
CF6-80A2	GE	298.15	249.34	84.79	19.84	0.30	0.37	0.45	6.28
CF6-80C2A2	GE	341.40	275.40	90.87	27.38	0.07	0.08	0.20	8.99
CF6-80C2B6	GE	341.14	275.27	90.74	27.38	0.07	0.08	0.20	8.99
CF6-80C2D1F	GE	337.83	268.39	85.36	26.01	0.08	0.10	0.21	9.96
CFM56-3	GE (SNECMA)	134.92	11.51	44.71	16.01	0.04	0.05	0.10	1.83
ALF 502R-5	Avco/Lycoming	47.37	39.09	13.68	5.40	0.06	0.05	0.22	5.39
JT8D-7/7A/7B	Pratt & Whitney	130.85	107.32	37.84	17.08	0.40	0.50	1.60	10.60
JT8D-9/9A	Pratt & Whitney	137.57	111.91	39.42	17.46	0.47	0.47	1.73	10.00
JT8D-15	Pratt & Whitney	155.82	125.00	45.01	19.54	0.25	0.25	1.57	10.33
JT8D-15A	Pratt & Whitney	164.68	131.88	46.83	19.44	0.66	0.75	1.86	9.57
JT8D-17A	Pratt & Whitney	155.16	123.60	43.70	18.53	0.25	0.30	0.64	2.02
JT9D-7F/7A	Pratt & Whitney	286.67	233.33	82.50	28.97	0.30	0.30	0.50	26.00
JT9D-7R4E/E1	Pratt & Whitney	280.16	228.04	86.36	29.23	0.16	0.13	0.13	1.11
JT9D-7R4E1(H)	Pratt & Whitney	293.39	241.93	84.66	29.17	0.15	0.13	0.22	3.35
JT9D-70/59/7Q	Pratt & Whitney	323.00	264.50	90.00	31.35	0.20	0.20	0.30	12.00
PW2037	Pratt & Whitney	203.44	167.46	52.78	18.65	0.05	0.06	0.21	2.26
PW4056/4156	Pratt & Whitney	309.79	255.29	87.04	27.51	0.06	0.01	0.13	1.92
PW4152	Pratt & Whitney	287.96	236.11	78.44	23.41	0.13	0.16	0.15	0.74
PT6A-27	P & W Canada	7.08	6.67	3.58	1.92	0.00	0.00	2.19	50.17
RB.211-535E4	Rolls Royce	256.03	199.74	75.40	25.13	0.69	0.94	1.33	2.85
SPEY MK555	Rolls Royce	74	60	23	12	1	1	5	72

Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Table F-41 (Cont.).

Jet Engine Model-Series	Manufact.	CO Emissions by Operating Mode (lbs/1,000 lbs)				NOx Emissions by Operating Mode (lbs/1,000 lbs)			
		Takeoff	Climbout	Approach	Taxi/Idle	Takeoff	Climbout	Approach	Taxi/Idle
CF6-6D	GE	0.50	0.50	6.50	54.20	40.00	32.60	11.40	4.50
CF6-50E/C1/E1/C2/E2	GE	0.50	0.50	5.70	81.30	36.50	29.60	9.70	2.40
CF6-80A2	GE	1.00	1.10	2.80	28.20	29.60	26.60	10.80	3.40
CF6-80C2A2	GE	0.52	0.52	1.93	41.65	34.38	22.86	9.11	3.79
CF6-80C2B6	GE	0.52	0.52	1.93	41.66	30.81	22.94	9.11	3.79
CF6-80C2D1F	GE	0.52	0.53	1.98	44.41	32.54	23.55	9.28	3.79
CFM56-3	GE (SNECMA)	0.90	0.90	3.50	31.00	18.50	16.00	8.40	3.90
ALF 502R-5	Avco/Lycoming	0.30	0.25	7.10	40.93	13.53	10.56	13.53	3.78
JT8D-7/7A/7B	Pratt & Whitney	1.50	2.00	10.50	35.50	17.10	13.50	5.50	2.70
JT8D-9/9A	Pratt & Whitney	1.24	1.66	9.43	34.50	17.92	14.21	5.64	2.90
JT8D-15	Pratt & Whitney	0.72	1.01	9.12	33.88	19.12	15.01	5.97	3.01
JT8D-15A	Pratt & Whitney	0.75	1.01	8.13	29.56	19.30	15.26	6.23	3.29
JT8D-17A	Pratt & Whitney	1.07	1.16	2.88	12.46	19.10	14.30	6.70	3.20
JT9D-7F/7A	Pratt & Whitney	0.40	0.40	2.90	54.00	46.00	34.40	7.80	3.10
JT9D-7R4E/E1	Pratt & Whitney	0.57	0.53	1.23	8.27	41.60	34.20	10.40	4.10
JT9D-7R4E1(H)	Pratt & Whitney	0.67	0.67	1.46	14.00	36.90	29.70	8.50	3.50
JT9D-70/59/7Q	Pratt & Whitney	0.20	0.20	1.70	53.00	31.60	25.60	7.80	3.00
PW2037	Pratt & Whitney	0.40	0.41	2.30	23.10	31.10	24.80	10.30	4.40
PW4056/4156	Pratt & Whitney	0.44	0.57	2.00	21.86	28.10	22.90	11.60	4.80
PW4152	Pratt & Whitney	0.12	0.17	1.09	12.76	26.90	22.70	11.10	4.90
PT6A-27	P & W Canada	1.01	1.20	23.02	64.00	7.81	7.00	8.37	2.43
RB.211-535E4	Rolls Royce	1.01	1.23	1.71	15.44	52.70	36.20	7.50	4.30
SPEY MK555	Rolls Royce	0	0	18	75	20	15	6	2

Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Table F-41 (Cont.).

Operating Mode	Time-In-Mode (minutes)	Fuel Flow (lbs/min)	Fuel Use (lbs)	Fuel Use Weights	Unweighted Emissions (lbs per 1,000 lbs fuel)			Emissions Weighted by Operating Mode Fuel Use Shares (lbs per 1,000 lbs fuel)		
					HC	CO	NOx	HC	CO	NOx
Takeoff	0.7	222.47	155.73	0.12	0.26	0.66	28.29	0.03	0.08	3.28
Climbout	2.2	176.34	387.95	0.29	0.31	0.75	22.15	0.09	0.22	6.40
Approach	4.0	62.53	250.13	0.19	0.92	5.52	8.73	0.17	1.03	1.63
Taxi/Idle	26.0	21.14	549.67	0.41	14.20	36.97	3.53	5.81	15.13	1.45
TOTAL	32.90	482.48	1343.48	1.00	15.69	43.90	62.71	6.10	16.45	12.75
		(gal./min)	(gal.)		(lbs. per 1,000 gal. fuel)			(lbs. per 1,000 gal. fuel)		
TOTAL (gals.***)		77.82	216.69		97.26	272.18	388.82	37.82	101.97	79.04

*** pounds-to-gallons conversion factor is 6.2 lb/gal.

Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Table F-41 (Cont.).

Jet Engine Model-Series	Manufact.	Fuel Flow by Operating Mode (lbs/min)				HC Emissions by Operating Mode (lbs/1,000 lbs)			
		Takeoff	Climbout	Approach	Taxi/Idle	Takeoff	Climbout	Approach	Taxi/Idle
250B17B	Allison	4.42	4.08	1.42	1.05	0.26	0.37	5.18	20.16
T56-A-7	Allison	39.87	36.45	19.10	8.23	0.18	0.18	0.28	14.96
TF41-A-2	Allison	149.00	149.00	100.00	18.17	0.64	0.64	0.73	51.26
CF6-50E	GE	321.17	254.63	87.86	22.24	0.60	0.70	1.00	49.30
F404-GE-400	GE	473.28	134.71	109.02	10.40	0.13	0.31	0.35	58.18
J79-GE-10	GE	589.83	163.83	103.17	18.33	0.49	1.63	0.66	8.91
J85-GE-21	GE	177.50	53.33	20.00	6.67	0.10	0.25	2.56	24.25
TFE-731-2	Garrett	27.12	22.88	8.86	3.17	0.11	0.13	4.26	20.04
F100-PW-100	Pratt & Whitney	736.67	173.33	50.00	17.67	0.10	0.05	0.60	2.26
J52-P-8B	Pratt & Whitney	122.83	102.17	72.00	11.33	1.08	0.69	0.67	48.96
J52-P-408	Pratt & Whitney	157.98	95.87	42.45	12.98	0.57	0.67	1.40	28.33
JT8D-9/9A	Pratt & Whitney	137.57	111.91	39.42	17.46	0.47	0.47	1.73	10.00
TF33-P-3	Pratt & Whitney	166	122	63	14.10	0.30	0.40	3.79	91.96
F402	Rolls Royce	178.53	178.53	103.10	18.95	0.41	0.41	0.73	18.80
R-1820	Curtis Wright	19.43	14.37	5.38	1.48	94.68	48.49	5.57	150.56

Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Table 41 (Cont.)

Jet Engine Model-Series	Manufact.	CO Emissions by Operating Mode (lbs/1,000 lbs)				NOx Emissions by Operating Mode (lbs/1,000 lbs)			
		Takeoff	Climbout	Approach	Taxi/Idle	Takeoff	Climbout	Approach	Taxi/Idle
250B17B	Allison	7.81	9.02	48.59	97.30	6.60	5.96	2.24	1.43
T56-A-7	Allison	1.60	1.60	3.00	17.69	11.71	10.18	6.38	2.50
TF41-A-2	Allison	1.64	1.64	2.17	94.80	22.46	22.46	16.85	1.71
CF6-50E	GE	0.50	0.50	5.70	81.30	36.50	29.60	9.70	2.40
F404-GE-400	GE	23.12	1.05	1.09	137.34	9.22	25.16	14.80	1.16
J79-GE-10	GE	17.29	5.29	7.37	43.64	6.82	15.44	11.29	2.91
J85-GE-21	GE	36.40	21.56	46.25	159.00	5.60	5.00	2.92	1.25
TFE-731-2	Garrett	1.39	2.03	22.38	58.60	15.25	13.08	5.90	2.82
F100-PW-100	Pratt & Whitney	55.10	1.80	3.00	19.34	16.50	44.00	11.00	3.96
J52-P-8B	Pratt & Whitney	0.71	0.87	3.00	63.78	13.05	12.13	10.10	1.79
J52-P-408	Pratt & Whitney	1.47	3.18	11.12	55.96	12.32	8.38	7.17	2.38
JT8D-9/9A	Pratt & Whitney	1.24	1.66	9.43	34.50	17.92	14.21	5.64	2.90
TF33-P-3	Pratt & Whitney	1.30	1.80	9.01	88.53	11.00	9.00	7.30	1.77
F402	Rolls Royce	2.70	2.70	8.20	106.30	14.80	14.80	8.00	1.70
R-1820	Curtis Wright	531.73	435.03	384.83	474.16	1.72	2.09	6.50	0.00

Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Table F-41 (Cont.).

Operating Mode	Time-In-Mode (minutes)	Fuel Flow (lbs/min)	Fuel Use (lbs)	Fuel Use Weights	Unweighted Emissions (lbs per 1,000 lbs fuel)			Emissions Weighted by Operating Mode Fuel Use Shares (lbs per 1,000 lbs fuel)		
					HC	CO	NOx	HC	CO	NOx
Takeoff	0.5	220.10	101.80	0.18	6.67	45.60	13.43	1.21	8.24	2.43
Climbout	1.2	107.81	126.68	0.22	3.69	32.65	15.43	0.83	7.34	3.47
Approach	3.7	55.00	201.45	0.36	1.97	37.68	8.39	0.70	13.47	3.00
Taxi/Idle	11.0	12.15	133.48	0.24	39.86	102.15	2.05	9.44	24.20	0.48
TOTAL	16.29	395.06	563.41	1.00	52.20	218.07	39.30	12.18	53.25	9.38
			(gal.)		(lbs. per 1,000 gal. fuel)			(lbs. per 1,000 gal. fuel)		
TOTAL (gals.***)			90.87		323.62	1352.06	243.63	75.54	330.17	58.15

*** pounds-to-gallons conversion factor is 6.2 lb/gal.
Source: EPA, Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources

Look-Ahead Issues Concerning Aircraft Emission Factors

Among the factors expected to influence aircraft emission rates in a forecasting context are the following:

- new aircraft engine designs,
- airport noise regulations,
- an increase in airport congestion problems

Aircraft with cleaner and more energy-efficient engine designs are expected to continue to slowly penetrate the world aircraft fleet population. Since there is a significant engineering and development leadtime for producing new aircraft engines, most of the commercial aircraft to be added to the fleet in the next five to seven years will be powered by engines currently monitored by the EPA.[82] Given the 12-year average service life for commercial aircraft engines, the newer generation of aircraft engines are not expected to make a significant impact on national emission levels until 2010. However, a possible catalyst for an increased rate of new aircraft engine market penetration is the recent enactment of national airport noise regulations, which require the phase-out of loud aircraft by 2000. Airlines are expected to upgrade their fleets with quieter and cleaner engines once the industry formulates compliance plans. The extent of the emission rate impact of such fleet upgrading is unknown at this time.

Acting as a counterweight on the downward pressure on emission rates caused by stock turnover and new regulations is the growth in air travel combined with limited excess capacity at many airports. Air travel has experienced strong growth over the past several years, and this growth is expected to continue for the foreseeable future. The primary capacity squeeze will be felt at small feeder airports and regional hubs. Increased congestion at capacity-constrained airports will increase taxi/idle times, resulting in increased emissions per LTO.

Given these offsetting impacts on aircraft emissions, the emission factors listed in Table F-40 should be satisfactory for estimating future aircraft emission levels.

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[82] Ibid., p. 208.

Waterborne Vessel Emission Factors

Commercial Vessels

Table F-41 provides the EPA emission factors for domestic commercial motorships. These emission factors are reported in the AP-42 document. The emission factors are based on Army Corps of Engineers waterway classification categories, which are defined as follows:

- **River** — All waterborne traffic between ports or landings wherein the entire movement takes place on inland waterways.

- **Great Lakes** — All waterborne traffic between United States ports on the Great Lakes.

- **Coastal** — All domestic traffic receiving a carriage over the ocean or between the Great Lakes ports and seacoast ports when having a carriage over the ocean.

To derived an average emission factor for all three waterway category vessels, a weighted-average methodology was applied whereby shipment tonnage and average length-of-haul data from the Army Corps of Engineers were used to construct emission factor weights.[83] Table F-41 provides more details on the weighting methodology.

The EPA *Nonroad Engine and Vehicle Emission Study Report* provides emission factors for two additional vessel categories: ocean-going steamships and harbor/fishing vessels.[84] These emission factors are based on engine sizes and operating mode (hoteling, cruise, and full power), and are not compatible with the emission factors provided in Table F-41. Because of the small emissions contribution of these vessels to the overall waterborne vessel total, they are not included in the composite waterborne vessel emission factors. For reference purposes, Appendix E.EM.D provides the ocean-going and harbor/fishing vessel emission factor tables from the Nonroad Engine and Vehicle report.

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[83] U.S. Army Corps of Engineers, *Waterborne Commerce of the United States, Calendar Year 1989* (Waterborne Statistics Center, New Orleans, LA, 1991), Part 5: National Summaries, pp. 32, 93.

[84] These emission factors were compiled and provided to the EPA in a Booz Allen & Hamilton report, *Commercial Marine Vessel Contributions to Emission Inventories* (Los Angeles, CA, October 7, 1991).

Table F-42. Commercial Vessel Emission Factors[85] (Pounds per 1,000 gallons of fuel)

Pollutant	Waterway Class			Weighted Average*
	River	Great Lakes	Coastal	
HC	50	59	50	51
CO	100	110	110	107
NO_x	280	260	270	273
SO_2	27	27	27	27

* Average emission factors calculated by multiplying pollutant emission factors for each waterway class by shipment mileage weights and then summing the weighted emission factor values. The shipment weights are as follows: River — 0.34, Great Lakes — 0.07, Coastal — 0.59. Shipment mileage weights were derived by multiplying tons shipped by the average length-of-haul per ton shipped for each waterway class.

Recreational Vessels

Table F-42 provides HC, CO, and NO_x emission factors for recreational marine vessels. These emission factors come from the EPA *Nonroad Engine and Vehicle Emission Study Report*. The EPA classifies and reports emission factors for the following vehicle/engine types:

- vessels with inboard engines (4-stroke)
- vessels with outboard engines (2-stroke)
- vessels with sterndrive engines (4-stroke)
- sailboats with auxiliary outboard engines (diesel)
- sailboats with auxiliary inboard engines (diesel)

When the AP-42 document was compiled, emission testing data was not available for recreational marine vessels. The EPA used coast guard diesel engine and automotive engine emission data to compute in-board emission factors based on the duty-cycle for engines classified as large out-boards. Out-board emission factors were derived from data supplied to the EPA by the Southwest Research Institute.

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[85] U.S. Environmental Protection Agency, *Compilation of Air Pollutant Emission Factors, Volume II: Mobile Sources*, AP-42, PB-87-205266 (EPA Office of Mobile Sources, September 1985), Part II, Off-Highway Mobile Sources, Table II-3.1.

U.S. Army Corps of Engineers, *Waterborne Commerce of the United States, Calendar Year 1989* (Waterborne Statistics Center, New Orleans, LA, 1991), Part 5: National Summaries, pp. 32, 93.

For the Nonroad Engine and Vehicle report, outboard engine emission factors were derived from test data supplied to EPA by the National Marine Manufacturers Association, which tested 25 two-stroke and three four-stroke outboard engines. For four-stroke outboards, emission factors recommended by the Southwest Research Institute were used for particulate matter emissions.[86] Since no data were available for 2-stroke outboard engine particulate matter emissions, EPA used emission factors from the CARB Technical Support Document for utility and lawn/garden equipment as approximations. For inboard/sterndrive gasoline engines, the EPA derived emission factors on the basis of test data on three 4-stroke gasoline marine inboard/sterndrive engines supplied by NMMA. The particulate emission factor used was 1.64 pounds per 1,000 gallons of fuel. The EPA used NMMA test data for a small diesel sailboat inboard and three large diesel inboard engines as the basis for calculating emission factors for inboard diesel engines.

As with the commercial marine vessels, vessel/engine-type emission factors must be weighted according to an activity or population level indicator and summed to obtain an average emission factor for the total recreational marine vessel population. Engine population data for each vessel/engine-type class was used to construct the weights. Boat population figures were gathered from local boat registration data bases, and were subsequently adjusted to obtain engine population estimates. Energy and Environmental Analysis developed the engine number derivation methodology for the EPA.

Table F-43. Recreational Marine Vessel Emission Factors[87] (Pounds per 1,000 gallons of fuel)

Pollutant	Vessel/Engine Type				Weighted Average*
	Outboard/ 2-Stroke	Outboard/ 4-Stroke	Sterndrive/ 4-Stroke	Sailboard/ Diesel Aux.	
HC	1610	190	160	50	1233
CO	2990	3130	2680	80	2884
NO_x	20	150	100	380	44

* Weights for each vessel/engine-type category were constructed from the following engine population figures: Outboard/2-Stroke — 8,204,304, Outboard/4-Stroke — 41,228, Sterndrive/4-Stroke — 2,713,420, Sailboat/Diesel-Aux. — 114,502.

[86] U.S. Environmental Protection Agency, *Designation of Areas for Air Quality Planning Purposes*, 40 CFR Part 81, Final Rule, Washington, D.C., Office of Air and Radiation, November 6, 1991.

[87] U.S. Environmental Protection Agency, *Nonroad Engine and Vehicle Emission Study —Report*, EPA 460/3-91-02 (EPA Office of Mobile Sources, November 1991), Table 2-03, Appendix I, Table I-11.

Table F-44. Ocean-Going Commercial Vessel Emission Factors

OPERATING PLANT Operating Mode/Rated Output	POLLUTANT				
	NO_x	HC	CO	SO_2	PM
STEAM PROPULSION					
Full Power	63.6	1.72	7.27	159x(%S)	56.5
Maneuver/Cruise	55.8	0.682	3.45	159x(%S)	20
Hotelling					
- Burning residual bunker fuel	36.4	3.2	*	159x(%S)	10
- Burning distillate oil	22.2	3	4	142x(%S)	15
MOTOR PROPULSION					
All underway operating modes	550	24	61	157x(%S)	33
AUXILLARY DIESEL GENERATORS					
- 20 KW (50% Load)	477	144	53.4	27	17
- 40 KW (50% Load)	226	285	67.6	27	17
- 200 KW (50% Load)	140	17.8	62.3	27	17
- 500 KW (50% Load)	293	81.9	48.1	27	17

Notes:
1) Emissions factors showing an asterisk (*) are considered negligible for these operating modes.
2) Average sulfur concentrations used are 0.8 percent for marine diesel, and 2.0 percent for bunker fuel oil.

Sources:
1) U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors, 1985.
2) U.S. Department of Transportation, Port Vessel Emissions Model, 1986.
3) California Air Resources Board, Report to the California Legislature on Air pollutant Emissions from Marine Vessels.

Table F-45. Harbor and Fishing Vessel Emission Factors

OPERATING PLANT Operating Mode/Rated Output	POLLUTANT				
	NO_x	HC	CO	SO_x	PM
DIESEL ENGINES	Pounds per Thousand Gallons of Fuel Consumed				
< 500 Horsepower					
Full	275.1	21	58.5	157x(%S)	17
Cruise	389.3	51.1	47.3	157x(%S)	17
Slow	337.5	56.7	59	157x(%S)	17
500 - 1000 Horsepower					
Full	300	24	61	157x(%S)	17
Cruise	300	17.1	80.9	157x(%S)	17
Slow	167.2	16.8	62.2	157x(%S)	17
1000 - 1500 Horsepower					
Full	300	24	61	157x(%S)	17
Cruise	300	24	61	157x(%S)	17
Slow	300	24	61	157x(%S)	17
1500 - 2000 Horsepower					
Full	472	16.8	237.7	157x(%S)	17
Cruise	623.1	24	44.6	157x(%S)	17
Slow	371.3	24	122.4	157x(%S)	17
2000+ Horsepower					
Full	399.6	21.3	95.9	157x(%S)	17
Cruise	391.7	16.8	78.3	157x(%S)	17
Slow	419.6	22.6	59.8	157x(%S)	17
GASOLINE ENGINES	Grams per Brake Horsepower Hour				
Exhaust Emissions - All HP Ratings	5.16	6.68	199	0.268	0.327
Evaporative Emissions		62.0	Grams/Hr		
Crankcase Blowby		38.3	Grams/Hr		

Notes: 1) Average sulfur concentration for marine diesel fuel = 0.8 percent.

Sources:
1) U.S. Environmental Protection Agency. Compilation of Air Pollutant Emission Factors, 1985.
2) U.S. Department of Transportation, Port Vessel Emissions Model, 1986.
3) California Air Resources Board, Report to the California Legislature on Air pollutant Emissions from Marine Vessels.

MODEL DOCUMENTATION REPORT: TRANSPORTATION SECTOR MODEL OF THE NATIONAL ENERGY MODELING SYSTEM

Appendix G - Supplement

March 1994

Office of Integrated Analysis and Forecasting
Energy Information Administration
US Department of Energy
Washington, DC

This report was prepared by the Energy Information Administration, the independent statistical agency within the Department of Energy. The information contained herein should not be construed as advocating or reflecting any policy position of the Department of Energy or any other organization.

Appendix G. Supplemental Reports

This Appendix consists of two unpublished reports produced by Energy and Environmental Analysis, Inc., under contract to Oak Ridge National Laboratory. These two reports formed the basis for the subsequent development of the Fuel Economy Model described in Volume I. They are included in order to document more completely the efforts undertaken to construct a comprehensive model of automobile fuel economy.

The supplemental reports are as follows:

Supplement 1: *Documentation of Attributes of Technologies to Improve Automotive Fuel Economy*

Supplement 2: *Analysis of the Fuel Economy Boundary for 2010 and Comparison to Prototypes*

DOCUMENTATION OF ATTRIBUTES OF TECHNOLOGIES TO IMPROVE AUTOMOTIVE FUEL ECONOMY

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TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1-1
2.	METHODOLOGY TO CALCULATED BENEFITS	2-1
	2.1 Overview	2-1
	2.2 Engineering Model	2-4
	2.3 Forecasting Methodology	2-11
	2.4 Calculation Procedure	2-17
3.	WEIGHT REDUCTION	3-1
	3.1 Engineering Description	3-1
	3.2 Front-Wheel Drive	3-2
	3.3 Material Substitution	3-5
4.	IMPROVEMENTS IN AERODYNAMICS	4-1
	4.1 Engineering Description	4-1
	4.2 Drag Reduction Potential	4-2
5.	TIRES, LUBRICANTS AND ACCESSORIES	5-1
	5.1 Tires	5-1
	5.2 Lubricants	5-2
	5.3 Accessories	5-3
6.	SPARK IGNITION ENGINE TECHNOLOGY	6-1
	6.1 Overview	6-1
	6.2 Overhead Cam Engines	6-5
	6.3 4-Valve Engines	6-8
	6.4 Fuel Injection	6-12
	6.5 Engine Friction Reduction	6-14
	6.6 Variable Valve Timing	6-18

TABLE OF CONTENTS

(Continued)

		Page
7.	IMPROVEMENTS TO AUTOMATIC TRANSMISSIONS	7-1
7.1	Engineering Description	7-1
7.2	Torque Converter Lock-up	7-4
7.3	Four/Five Speed Automatic Transmission	7-5
7.4	Electronic Transmission Control	7-9
7.5	Continuously Variable Transmissions	7-11
8.	DIESEL ENGINES AND TWO-STROKE ENGINES	8-1
8.1	Diesel Engines	8-1
8.2	Two-Stroke Engines	8-5
9.	POWER BOOSTING	9-1
9.1	Turbocharging	9-1
9.2	Other Supercharging Technologies	9-4

LIST OF TABLES

		Page
Table 2-1	Technology Definitions	2-2
Table 2-2	Technology/Energy Use Relationship	2-12
Table 2-3	Fuel Economy Cycle Characteristics	2-14
Table 2-4	Estimated Fuel Consumption Sensitivity Coefficients	2-16
Table 3-1	Weight Reduction Through FWD Conversion	3-6
Table 3-2	Weight Reduction Through Material Substitution	3-7
Table 3-3	Weight Reduction Potential For Mazda Familia Through Aluminum Use	3-11
Table 4-1	Drag Co-Efficients for Selected 1988 Vehicles	4-3
Table 5-1	Comparison of Electric to Hydraulic Power Steering on Acura NSX	5-4
Table 6-1	Engine Classification	6-3
Table 6-2	Effect of Number of Cylinders on Fuel Economy	6-17
Table 7-1	Typical Ratio Spreads for Transmissions in 1988	7-3
Table 7-2	Matched Pair Comparisons of Fuel Economy With Three- and Four-Speed Automatic Transmissions	7-8
Table 8-1	Comparison of Diesel/Gas Fuel Economy - 1987 Cars	8-4

LIST OF FIGURES

		Page
Figure 2-1	Vehicle Resistance in Coastdown Test	2-6
Figure 2-2	Proportion of Engine Friction Due to Valve Train	2-10
Figure 3-1	Packaging Efficiencies Between RWD and FWD as Measured By CURBWT/PVOL	3-4
Figure 6-1	Differences in Means for OHC, OHV and DOHC 4 Valve Engines by Domestic and Import Classifications	6-6
Figure 6-2	Differences in Means for OHC, OHV and DOHC 4 Valve Engines by Domestic and Import Classifications	6-7
Figure 6-3	Power Comparison	6-10
Figure 6-4	Improvement in Fuel Consumption Due to Needle Bearing Roller Type Rocker Arm	6-15
Figure 7-1	Vehicle Performance Vs. Fuel Economy	7-10

1. INTRODUCTION

Over the last decade, the Department of Energy (DOE) has been involved in forecasting automotive fuel economy to model fuel demand, and has also been active in estimating fuel economy potential to comment on regulatory initiatives. The single most important factor in future fuel economy projections is the technological improvement to cars, since size class mix shifts and changes to performance have traditionally had a much smaller effect on fuel economy relative to changes to vehicle technology. The DOE method of forecasting fuel economy relies on detailed understanding of technologies available to improve automotive fuel economy. Vehicle fuel economy changes associated with technological improvements are forecast assuming constant size and performance, and then adjusted to account for expected shifts in consumer preference for size and performance. This methodology was developed for the DOE by Energy and Environmental Analysis (EEA) and in new embodied in the model called the Technology/Cost Segment Model (TCSM).

The TCSM is largely an accounting model that tracks the various technologies and their synergies and non-additivity, so that forecasts of future fuel economy avoid the problem of double counting technology benefits or simultaneously utilizing non-additive technologies. However, the key inputs to the TCSM are the list and characteristics of available technologies. Over the last few years these technology definitions and attributes have been continuously refined, but no single report exists that contains a comprehensive documentation of the technologies and characteristics resident in the current TCSM. This report is intended to provide such a documentation so that technology characteristics are transparent to the TCSM user.

As noted, technology benefits are defined at constant vehicle acceleration performance, and at constant vehicle interior room as measured by EPA's interior volume index. Any technology can be utilized to increase these

vehicle attributes rather than fuel economy, or to provide some combination of benefits that meet the requirements for the market. Since the tradeoffs between fuel economy and performance as well as fuel economy and size are understood, an exogenous adjustment can be applied to calculate the net effect for changes to vehicle attributes that occur in combination with changes in technology.

The DOE forecasts have been a subject of much recent attention, and the technology benefits utilized in the TCSM has been subject to a very detailed review by major automanufacturers. In particular, Ford Motor Company has held several meetings with EEA to discuss differences between its findings on some technologies with the findings developed by EEA, especially if the views are divergent. Ford's inputs are discussed in detail in this report, and the reasons for remaining areas of disagreement are also provided. Other manufacturer inputs were not as detailed, and are referenced at various points in the documentation where appropriate.

Section 2 of this report provides an overview of the calculation procedure for forecasting future fuel economy, as well as its relationship to the exact engineering equations that can be used to compute fuel consumption as a function of vehicle related variables. Section 3 through 9 discuss various technology groups such as these effecting weight, the conventional spark injection engine, or transmissions. Each section provided a comprehensive review of:

- the technology's mechanical features
- the engineering reasons behind its fuel economy improvement potential
- actual data on the fuel economy improvement measured
- other related technology attributes that hinder or aid market penetration
- synergy or non-additivity constraints, if any, with other technologies considered.

One important aspect, the technology cost (or more accurately, its incremental retail price effect) is not documented in this report but will be issued separately as an addendum to this report.

2. METHODOLOGY TO CALCULATE BENEFITS

2.1 OVERVIEW

The fuel economy behavior of a vehicle is dependent not only on the individual technologies employed on a vehicle, but also in how they are applied, and to some extent, what other technologies are present simultaneously. As noted in the introduction, the fuel economy benefit due to technology changes to a given automobile is always calculated on the basis of holding vehicle size as measured by interior volume, and vehicle performance constant. The second term is more complex to define, but each technology that affects the power, torque or weight of the engine/vehicle is examined in detail, and the appropriate set of tradeoffs to measure fuel economy benefit on a constant performance basis are identified and defined.

Individual technology benefits are defined relative to a base technology and are estimated in terms of percent benefits to fuel economy. If the technology represents a change to a continuous variable e.g., weight, the impact of a specific (e.g. 10) percent change in the variable a fuel economy is estimated. If the technology represents a discrete technology, the percent benefit for that technology is defined relative to replacing a base technology (e.g., 4-valve engine over 2-valve engine) holding the size and performance parameters constant. Table 2-1 provides a list of technologies documented in this report and the baseline technology against which benefits are measured.

Of course, no technology will be used in isolation and synergistic and non-additivity constraint must be recognized. Non-additivity is handled simply by recognizing the fact that the sum of market penetration of two non-additive technologies can never exceed 100 percent, i.e., both technologies cannot be present in the same car. Synergy is recognized from engineering analysis which identifies technologies that simultaneously contribute to the reduction

TABLE 2-1

TECHNOLOGY DEFINITIONS

Technology	Definition
Front Wheel Drive	Benefits include effect of weight reduction and engine size reduction starting from a late-1970's rear-wheel drive vintage design.
Drag Reduction I	Based on C_D decreasing from 0.375 in 1987 to 0.335 in 1995, on average.*
Drag Reduction II	Based on C_D decreasing from 0.335 to 0.30 in 2001, on average.*
Torque Converter Lock-up	Lock-up in gear 2-3-4 compared to open converter.
4-Speed Auto Transmission	3-speed auto transmission at same performance level.
Electronic Transmission Control	Over hydraulic system, with electronic control of shift schedule and lock-up of torque converter.
Accessory Improvements	Improvements to power steering pump, alternator, and water pump over 1987 baseline.
Lubricants (5W-30)	Over 10W-40 oil.
Weight Reduction	Based on substituting advanced materials for conventional materials, while maintaining the same strength and size.

* To exploit the benefits of drag reduction, the top gear must have a lower (numerical) ratio to account for the reduced aerodynamic horsepower requirement.

TABLE 2-1

TECHNOLOGY DEFINITIONS

(Continued)

Technology	Definition
Overhead Camshaft	OHV engine of 44-45 BHP/liter replaced by OHC engine of 50-52 BHP/liter but with smaller displacement for constant performance.
Roller Cam Followers	Over sliding contact follower.
Low Friction Pistons/Rings	Over 1987 base (except for select engines already incorporating improvement).
Throttle Body Fuel Injection	Over carburetor (includes air pump elimination effect).
Multi-Point Fuel Injection	Over carburetor. Includes effect of tuned intake manifold, sequential injection and reduced axle ratio for constant performance.
4-Valve Engine (OHC/DOHC)	Over two-valve OHC engine of equal performance. Includes effect of displacement reduction and compression ratio increase from 9.0 to 10.0.
Tires	Over 1987 tires, due to improved construction.
Intake Valve Control	Lift and Phase Control for intake valves. Includes effect of engine downsizing to maintain constant performance.
Advanced Friction Reduction	Includes composite con rod, titanium valve springs, light weight reciprocating components.

of the same source of energy loss. The computational methodology uses a linearized form of the exact engineering equation, and it is described below.

Clearly, the method is an approximation to make the calculations relatively simple, yet yields results that have been accurate to ±0.2 MPG, historically. In projecting a maximum technology boundary case for the post-2000 time frame it is believed that these approximations could cause larger errors and a more rigorous engineering model is required. The current model is described below.

2.2 ENGINEERING MODEL

The model follows the work of Sovran[1/2/] who produced a detailed analysis of tractive energy requirements on the EPA fuel economy test schedule, i.e., the city cycle and the highway cycle. Each driving cycle specifies speed as a function of time. The force required to move the vehicle over the driving cycle is easily derived from Newton's laws of motion:

$$F = M\, dV/dt + R + D$$

where F = the force required

M = the vehicle mass

dV/dt = the acceleration rate

R = the tire rolling resistance

D = the drag force

From the knowledge of physics, it can be shown that:

$$F = MdV/dt + gMC_RV + C_D \frac{A\rho V^2}{2} \quad \text{-- (1)}$$

where C_R is the rolling resistance co-efficient

C_D is the drag coefficient

g, ρ are the gravitational acceleration and air density respectively.

V is the vehicle speed

A is the vehicle frontal area

Over the fuel economy test, V is specified as V(t), and the energy required is the integral of force over distance, s:

$$E = \int F.\ ds$$

$$= \int F.\ V.\ dt.$$

In the car, energy is provided only when F is greater than zero, while energy during deceleration is simply lost to the brakes. Taking these factors into account, Sovran and Bohn[2/] showed that energy per unit distance (S)

$$E/S = \alpha MC_R + \beta C_D A + \delta M \quad --- (2)$$

where α, β and δ are constants virtually independent of vehicle characteristics, but are different for the city and highway cycle. In essence, each term represents one component of the total force, the first representing energy to overcome tire rolling resistance, E_R, the second to overcome aerodynamic drag, E_A, and the third to supply kinetic energy of acceleration, E_k. In the absence of acceleration (during steady speeds) E_k is zero. Figure 2-1 shows the drag and the rolling resistance forces for a typical car at steady state cruise, as well as the driveline loss described below.

Sovran [1/] also related tractive energy to fuel consumption by adding the work required to drive accessories, and the energy wasted by the engine during idle and braking. He defined the average engine brake specific fuel consumption over the test cycle as bsfc, and derived the following equation

$$FC = \frac{bsfc}{\eta_d} [E_r + E_A + E_k] + bsfc\ E_{AC} + G_i\ (t_i + t_b) \quad . . . . \quad (3)$$

where η_d is the drive train efficiency

E_{AC} is the accessory energy consumption

G_i the idle fuel consumption rate

t_i, t_b the time at idle and braking in the test cycle.

Vehicle Resistance in Coastdown Test

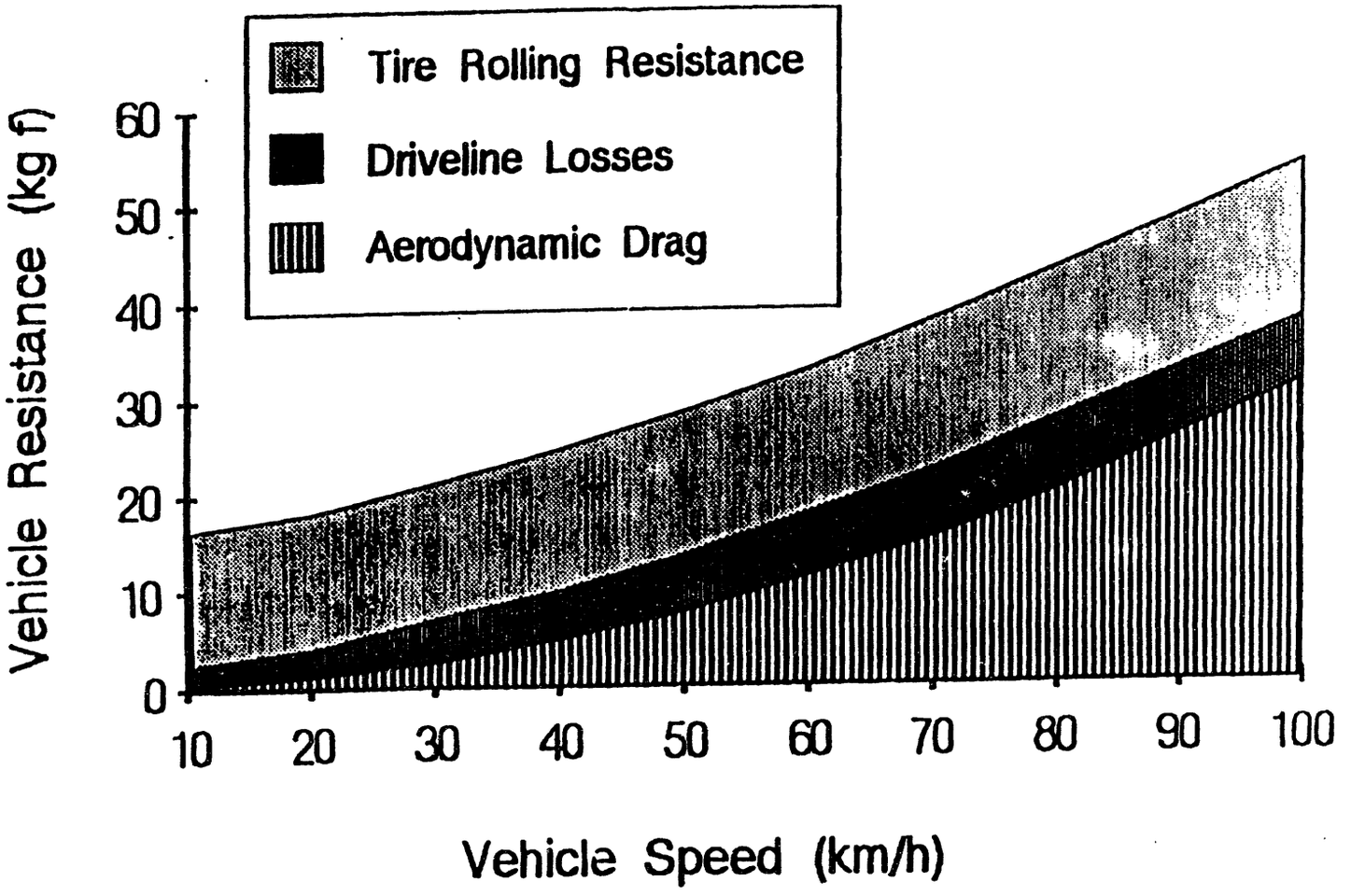


FIGURE 2-1

The above equation shows that reductions in rolling resistance, mass, drag and accessory energy consumption, and idle fuel consumption cause <u>additive</u> reductions in fuel consumption.

The engine output energy is supplied to match the tractive energy requirements. If total energy required is defined as

$$E = \frac{1}{\eta_d} [E_A + E_R + E_k] + E_{AC} \quad . . . \qquad (4)$$

then $E = \overline{BHP}.t$ (engine power output)

Engine output power can be further decomposed to provide explicit recognition of engine internal losses. There are no conventions regarding the nomenclature of such losses. In general, the engine has two types of losses, one arising from the thermodynamic efficiency of combustion and heat recovery, and the second due to friction, both mechanical and aerodynamic. Aerodynamic friction is more usually referred to as pumping loss.* A third component that is sometimes excluded from the engine efficiency equation is the power required to drive some internal accessories such as the oil pump and the distributor. Items such as the water pump, alternator and fan are usually (though not always) classified under accessory power requirements. In this analysis, power for all accessories - both internal and external - are classified under accessory power requirements, and the following relationship holds:

$$\overline{BHP} = \overline{IHP} (1 - P - F_r) \quad . . . \qquad (5)$$

Where $\overline{IHP}$ is power generated by the positive pressure in the cylinder

P is the pumping loss fraction

---

* We distinguish between throttling loss and pumping loss, using the latter term to include both throttling loss and frictional losses in the exhaust and intake system.

F_r is the mechanical friction loss fraction

Since fuel consumption, FC, can be written as

$$FC = \overline{bsfc} \cdot BHP \cdot t = \overline{isfc} \cdot IHP \cdot t$$

$$\overline{bsfc} = \frac{\overline{isfc}}{(1-P-Fr)} \quad . . . \qquad (6)$$

Substituting equation (6) into (3) we obtain

$$FC = \frac{\overline{isfc}}{1-P-F_r} [E_R + E_A + E_k + \eta_d E_{ac}] + G_i [t_i + t_b] \quad . . . \qquad (7)$$

The isfc is principally a function of combustion chamber design and compression ratio of the engine, and to a lesser degree, the air fuel ratio. Since nearly all cars operate at stoichiometry, the air fuel ratio is currently not a factor but could become one if "lean-burn" concepts are utilized.

Pumping losses are dependent principally on the relative load of the engine over the cycle. The larger the engine for a given car weight, the lower the load factor and the higher the pumping loss due to throttling. Pumping losses are also incurred in the intake and exhaust manifolds and valve orifice. The use of tuned intake and exhaust manifolds, and greater valve area (e.g. by utilizing 4 valves/cylinder) reduce pumping losses. Losses other than throttling loss are not unimportant in the contribution to overall pumping loss.

Engine mechanical friction is associated with the valve train losses, piston and connecting rod friction, as well as the crankshaft friction. At low RPM, valve train friction is quite large as a percent of total friction, but decreases at higher RPM, while piston/connecting rod friction increases

Idle fuel consumption is also affected by changes in engine parameters. At idle, all of the fuel energy goes into driving the accessories and overcoming pumping and friction loss, since there is no output energy requirement. Hence, decreases in pumping loss or mechanical friction result in much larger percentage reduction in fuel consumption at idle than at load.

Mitsubishi provided data on the general components of friction of the engine as shown in Figure 2-2. The pumping loss shown here is due to internal airflow and not due to throttling. At closed throttle idle pumping loss is approximately equal to frictional loss.

Equation 7 also shows the general structure of the calculation procedure. A simple differentiation of (7) yields:

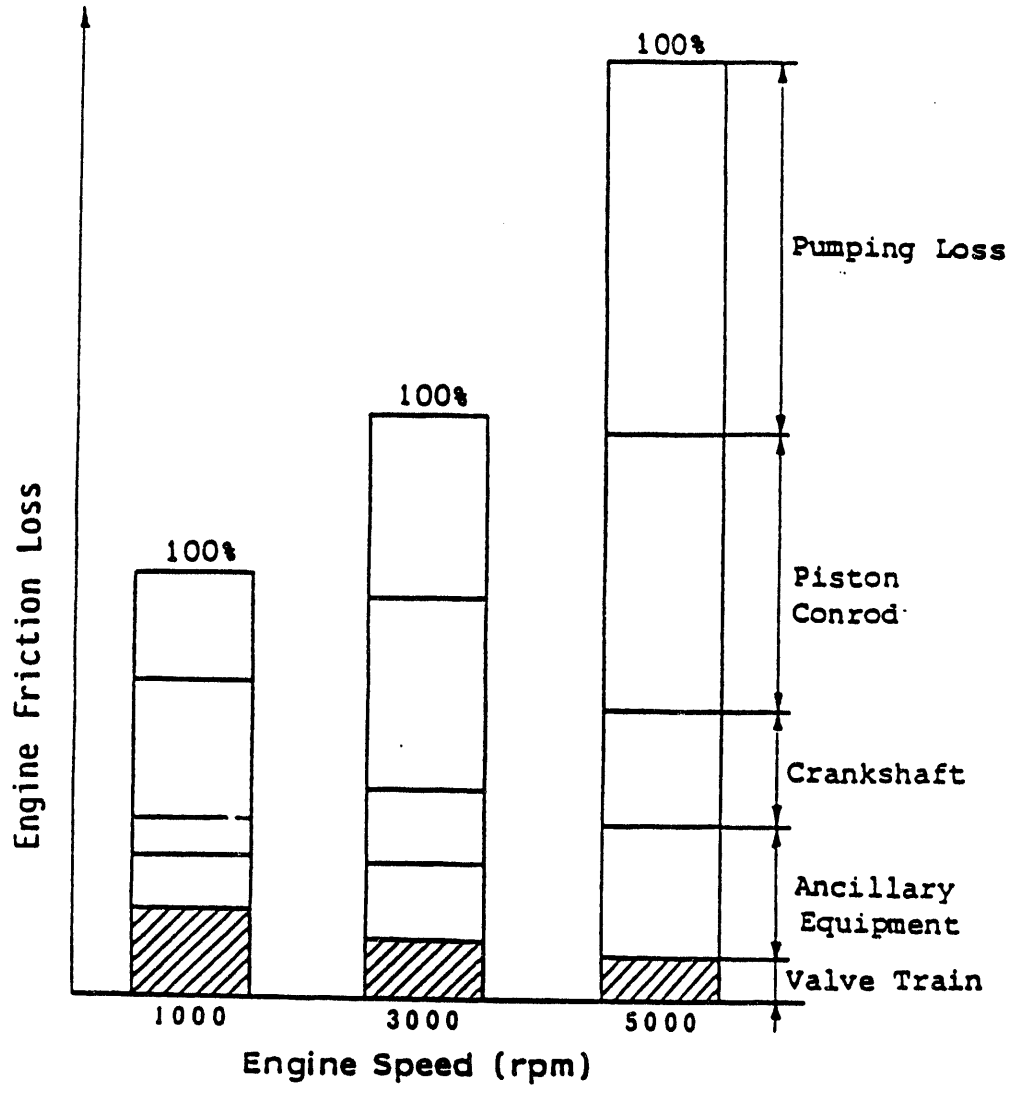
$$\frac{dFC}{FC} = \frac{d(\overline{isfc})}{isfc} + \frac{P}{1-P-F_r} \bullet \frac{dP}{P} + \frac{F_r}{1-P-F_r} \bullet \frac{dF_r}{F_r}$$

$$+ \frac{E_A}{E_A+E_R+E_k + \eta_d E_{AC}} \bullet \frac{dE_A}{E_A} + \ldots + \ldots \qquad (8)$$

where each derivative is expressed as a percentage change. Thus, a one percent change in isfc translates to a one percent change in fuel economy, but a one percent change in pumping loss must be weighted by the fraction that pumping loss is of total output energy. Similarly, aerodynamic tractive energy change must be weighted by the fraction that aerodynamic energy loss is of total tractive energy.

Two observations are required at this point. First, equation (8) assumes that the vehicle can be reoptimized for any change, so that engine variables are not affected by tractive energy requirements. As pointed out by Sovran, this

FIGURE 2-2



Proportion of Engine Friction Due to Valve Train

With Roller-Cam Followers

is not always possible. For example, aerodynamic losses are near zero at low speed but high at high speed. Hence, an engine cannot be simply downsized as aerodynamic loss is reduced, since the smaller engine will not have enough power at low speed. As a result, a higher gear must be added along with engine downsizing to achieve a correct compromise. In theory, it is possible to reoptimize the entire drivetrain, but in practice compromises cause significant losses in fuel economy from the attainable maximum. In the long run, as for 2010, some factors can indeed be optimized to yield the full predicted value, while other factors cannot. For example, it appears unlikely that predicted friction loss reduction related fuel savings can be obtained as the engine cannot be downsized to the point where low speed torque is compromised. On the other hand, rolling resistance decreases may provide the predicted fuel savings as its effect is felt uniformly throughout the speed range.

2.3 FORECASTING METHODOLOGY

Methods to increase the fuel economy (reduce fuel consumption) must rely on reduction of energy contributed by each of the terms shown in Equation (7). Equation (8) is useful if the change in factors is small, but not applicable for the large changes. Focusing on the terms in equation (7) it is easily seen that fuel consumption is decreased by:

- decreasing friction and pumping loss
- decreasing weight
- decreasing drag
- decreasing rolling resistance
- decreasing accessory power consumption
- decreasing idle fuel consumption

Of course, a given technology can act on more than one of these factors simultaneously. Table 2-2 shows the relationships between individual technologies and the terms listed in equation (7). Drivetrain efficiency, η_d is <u>not</u>

TABLE 2-2

TECHNOLOGY/ENERGY USE RELATIONSHIP

	ISFC	P	F_r	E_A	E_R	E_K	E_{AC}	G_1	η_d
Weight Reduction					✓	✓			
Drag Reduction				✓					
4-speed Automatic		✓	✓						✓
TCLU									✓
Electronic Trans Control		✓	✓						
Accessory Improvements							✓		
Tires improvement					✓				
5W-30 oil			✓						
Overhead cam	✓	✓	✓					✓	
Roller Cam Followers			✓					✓	
Low Friction Piston/Rings			✓					✓	
Fuel Injection	✓	✓						✓	
4-valves/cylinder	✓	✓						✓	
Intake Valve Control		✓							✓
5-speed Automatic		✓	✓						
Electric Power Steering							✓		

the major factor in the benefits associated with multi speed transmissions; rather, the reduction in pumping and frictional losses are the biggest factor. It should also be noted that all engine improvements affect idle fuel consumption, so that idle consumption can be approximated with E_I, an "equivalent" energy at idle to drive the accessories and torque converter. E_I is simply a mathematical artifact to make the analysis simpler for forecasting. Hence, we have fuel consumption.

$$FC = \frac{\overline{isfc} \quad [E_R + E_A + E_K + \eta_d (E_{AC} + E_I)]}{\eta_d \ [1-P-F_r]} \quad . \ . \ . \qquad (9)$$

The relationship between fuel consumption and vehicle variables can be derived from equation 7 in exact terms if the co-efficients are evaluated for the FTP and HIGHWAY driving cycles. In fact, Sovran utilized a detailed evaluation of these cycles to derive the sensitivity of fuel consumption to vehicle weight, aerodynamic drag and tire rolling resistance coefficient. The general characteristics of the two cycles are shown in Table 2-3. One striking factor is that nearly 41 percent of the time on the FTP is spent in deceleration or at idle. In comparison, less than 10 percent of the time on the highway cycle is spent in braking or at idle. This difference, coupled with the different speeds and average acceleration rates in each cycle, leads to substantially different sensitivities between the two cycles.

In order to evaluate the sensitivity of fuel consumption to changes in vehicle parameters, information is required on the fuel consumption at idle and braking as well as the fuel consumed by driving accessory loads. Sovran utilized data on 1979/1980 GM cars and found that idle and braking fuel consumption was proportional to engine size. As an approximation, he assumed idle + braking consumption to be a constant fraction of total fuel consumed and estimated this fraction at 16 percent for the FTP and 2 percent for the highway cycle. He utilized a similar assumption for the accessory fuel

TABLE 2-3

FUEL ECONOMY CYCLE CHARACTERISTICS

	Urban	Highway
Speed (average) kmh	38.4	77.6
Speed (max) kmh	91.5	96.8
Distance, km	12.0	16.5
Time at idle (s)	249	3
Time of braking (s)	311	57
Total time for cycle (s)	1373	765
Percent of time at idle and braking	40.8	9.84

consumption fraction, holding it constant at 10 and 9 percent respectively. This is equivalent to the approach in Equation (9) where the term $[E_{AC} + E_I] \cdot$ bsfc is replaced by a constant. Utilizing these assumptions, he derived sensitivity coefficients that were dependent on the drag to mass ratio and the rolling resistance coefficient. Using typical value for the average 1988 car, with a mass of 1400 kg (3100 lb), C_D of 0.37, frontal area of 1.9 m^2 and tire rolling resistance co-efficient of 0.01, the fuel consumption sensitivity coefficients from equation 2 are as follows:

β = 0.28

δ = 0.54

$\mathfrak{L}$ = 0.24

The weight reduction sensitivity co-efficient above does not incorporate the effect of engine downsizing, which reduces idle/braking fuel consumption proportionally. The coefficients assume that the engine and drivetrain are adjusted to provide <u>constant bsfc</u>, (a factor which may not be realized in practice) but do not account for engine downsizing. Second, the constants are dependent to a certain extent on the assumptions for the fraction of fuel consumed at idle + braking, and by accessory power demands. (The smaller these fractions, the larger the sensitivity coefficients).

Table 2-4 provides a summary of the estimates of the EEA estimated sensitivity coefficients that is attained in actual practice, as opposed to the estimates derived purely from equation (8). In the application of these coefficients, it should be recognized that they can be used only for modest variations for any of the variables involved.

When large reductions of any variable are likely to occur the preferred form of analysis is to use equation (7) with a "slippage" factor to account for the fact that theoretical benefits cannot be attained in actual practice for some variables of concern.

TABLE 2-4

ESTIMATED FUEL CONSUMPTION SENSITIVITY COEFFICIENTS

(Percent reduction in fuel consumption per percent reduction in independent variable.)

Variable	FC Sensitivity	F/E Sensitivity
Weight reduction	0.62* (0.54)	0.66
Drag reduction (C_D)	0.22	0.23
C_R reduction	0.23	0.24
Thermal efficiency	1.00	1.00
Pumping loss	0.23	0.24
Friction loss	0.23	0.24
Drivetrain efficiency	0.78	0.81
Accessory power	0.10	0.11

* Includes proportional reduction of displacement.

The methodology used to calculate the fuel economy benefit due to the application of any set of technologies to the automobile is as follows. First, the technology set is examined to identify which energy use factors are affected, and areas of overlap are examined for synergy. Second, the net reduction in each specific energy use area are estimated and the benefits to fuel consumption calculated with equation (8). In general, synergies occur primarily in pumping loss reduction, with smaller synergies in the area of friction reduction.

2.4 CALCULATION PROCEDURE

The theoretical concepts behind the forecast have been explained through the engineering equations. The exact method of calculating fuel economy involves a sequence of steps that are as follows:

- Definition of a baseline
- Identification of available technology
- Adoption of technology to the proper level of market penetration
- Calculation of fuel economy after adoption of technology

The analysis can be performed at the model specific (such as Ford Escort or Chevrolet Caprice) level or at a more aggregate market class level, where vehicles within a market class are very similar in size, performance and option levels.

The starting point of all the analysis is the definition of a baseline of vehicle technology and fuel economy that is derived from actual data. For example, the choice of the 1988 Ford Escort as the baseline requires the identification of all the vehicle characteristics such as weight, drag coefficient, engine size and power, types of transmissions, acceleration performance, type of fuel system, etc, as well as the actual EPA composite fuel economy rating for 1988. If the analysis is at a market class level, these characteristics are averaged across all models in the given year, and

discrete technologies such as 4-speed automatic transmissions are described by their market share within the class.

Once the baseline technologies are detailed, a list of available technologies is identified along with the potential date of availability. In the short term, most technologies available for improvement are dictated by the product plan for a particular model, and these are tracked through articles in the trade press. In the longer term, EEA selects available technologies based on both product lifecycle of the model, as well as technology readiness. Continuing with the Ford Escort as the example, it's product lifecycle is eight to nine years, and a new design was introduced in 1990. This implies that major changes can be made when the next model is introduced in 1998/1999.

Technology readiness is based on a determination by EEA of when a technology is likely to be broadly adopted in the marketplace. For example, we expected that 4-valve per cylinder technology could be broadly adopted by domestic manufacturers in the 1991-1998 timeframe, whereas 5-valve/cylinder technology is unlikely to enter the mainstream until 2001. Such determinations are based on interviews with sta utomanufacturers and involves some degree of subjective judgement. recognized that technology availability does not guarantee its introduction in the marketplace, but depends on the costs of a technology and its benefits. A simple model of technology adoption by the manufacturers is one where technology is adopted in a carline if the value of fuel saved over a specific period exceeds its first cost to the consumer. Analysis of historical data suggests that a period of 4 years (typical of new car ownership) for calculating the payback provides a good historical approximation of manufacturer behavior, and we have utilized this to represent scenarios of business as usual or "product plan" scenarios. Other scenarios can be easily constructed to evaluate technology adoption based on fuel savings over a vehicle lifetime (10 or 12 years), or in total disregard of any costs effectiveness criteria where all available technologies are adopted to the maximum extent possible.

Technology adoption is usually associated with a level of market penetration. For most technologies, it is an "all-or'nothing" decision at the carline level, since, for example, a given car can either have a new low drag body or it will not. Technology non-additivity must be accounted for so that two technologies (such as manual and automatic transmissions) that can not be present in the same car are not assumed to each have 100 percent market penetration. However, there are some technologies that are offered as options in a given model, where the consumer has a choice. Typically, these involve performance engines or engines using other fuels such as diesel engines. Evaluation of their market penetration is either developed by specific scenarios assumptions, or else determined by trend analysis or results from consumer surveys if the object is to forecast fuel economy.

The calculation of fuel economy after technology adoption is relatively simple using the "linarized" method detailed earlier, but specific adjustments are made for synergistic effects between two technologies. The synergies are recognized through engineering analysis, as the operation of each technology is well understood and the source of its benefits (in terms of reduction of specific losses identified in the engineering equations) are known. In brief, the model is:

$$FC = FC_o \, [1 + \sum m_i x_i + \sum_i \sum_j s_{ij} \, m_i m_j]$$

where: FC_o is the baseline fuel economy

m_i is the market penetration of the ith technology

x_i is the percent fuel economy benefit of the ith technology

s_{ij} is the synergistic effect between technology i and j on fuel economy.

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3. WEIGHT REDUCTION

3.1 ENGINEERING DESCRIPTION

One of the most important determinants of vehicle fuel economy is vehicle weight. Lower vehicle reduces the forces required to accelerate a car, which in turn reduces fuel consumption. There are four principal methods to reduce vehicle weight, namely:

- Conversion to front-wheel drive
- Downsizing
- Material substitution
- Use of unit body construction

Conversion to front-wheel drive reduces weight because: 1) the driveshaft and rear axle are eliminated, and 2) a vehicle of given interior room can have smaller exterior dimensions due to more efficient packaging.

Downsizing reduces vehicle weight by decreasing the size. This process, however, does not conserve interior room for cars, and results in a loss of consumer utility. It is not considered in this report, since its effects can be simulated as a changed mix of size classes.

Material substitution requires the substitution of high strength steel, aluminum, magnesium alloys or plastics for plain carbon steel, which accounted for over 45 percent of 1988 vehicle weight. In most cases, this involves redesign of the part to optimize for strength.

Unit body construction refers to the elimination of the conventional chassis/body structure. Prior to 1978, most vehicles utilized a separate chassis that carried all vehicle loads, and the body was suspended on the chassis. Unit body vehicles utilize the body panels as stressed members that carry the vehicle load. Elimination of the chassis results in a 5-8 percent

reduction in vehicle empty weight. Between 1980 and 1983, many U.S. domestic cars have incorporated all four methods of weight reduction described below. All front wheel drive cars now feature unit body construction.

Conversion to front-wheel drive began in the U.S. with the introduction of the Omni/Horizon in 1978 and the GM X-car in 1979. In general, most of these conversions have maintained interior volume in comparison to their rear-wheel drive predecessors, thus permitting comparisons of fuel economy gains and cost changes.

Downsizing occurred primarily during the 1975-1980 era in the U.S. Even though the exteriors of the cars are now much smaller, interior volume declined only modestly. (This downsizing does not account for "mix shift" which is treated separately). More recently, cars are being upsized and recent cars have even increased in exterior dimensions in almost all countries around the world.

3.2 FRONT-WHEEL DRIVE

In front wheel drive (FWD) vehicles, the engine/transmission output shaft is directly connected to the front-wheels, and the most common placement of the engine is in the transverse position, so that the crankshaft is parallel to the driveshaft. In contrast, the engine/transmission in rear wheel drive (RWD) vehicles is placed longitudinally. The output shaft is connected to the rear axle by a propeller shaft that runs from the front to the rear. The pair is transmitted to the wheels via the differential. The advantages of FWD over RWD designs are:

(1) The transverse engine placement allows more compact packaging of the drivetrain, eliminating the propeller shaft, differential and rear axle.

(2) The vehicle's exterior dimension can be reduced significantly when the engine is packaged transversely, without impacting passenger room. In addition, FWD eliminates the hump in the floor required to accommodate the drive shaft, enhancing legroom.

(3) The drivetrain is made more efficient by the elimination of the less efficient hypoid gears in the rear drive axle with the helical gears used in the transaxle.

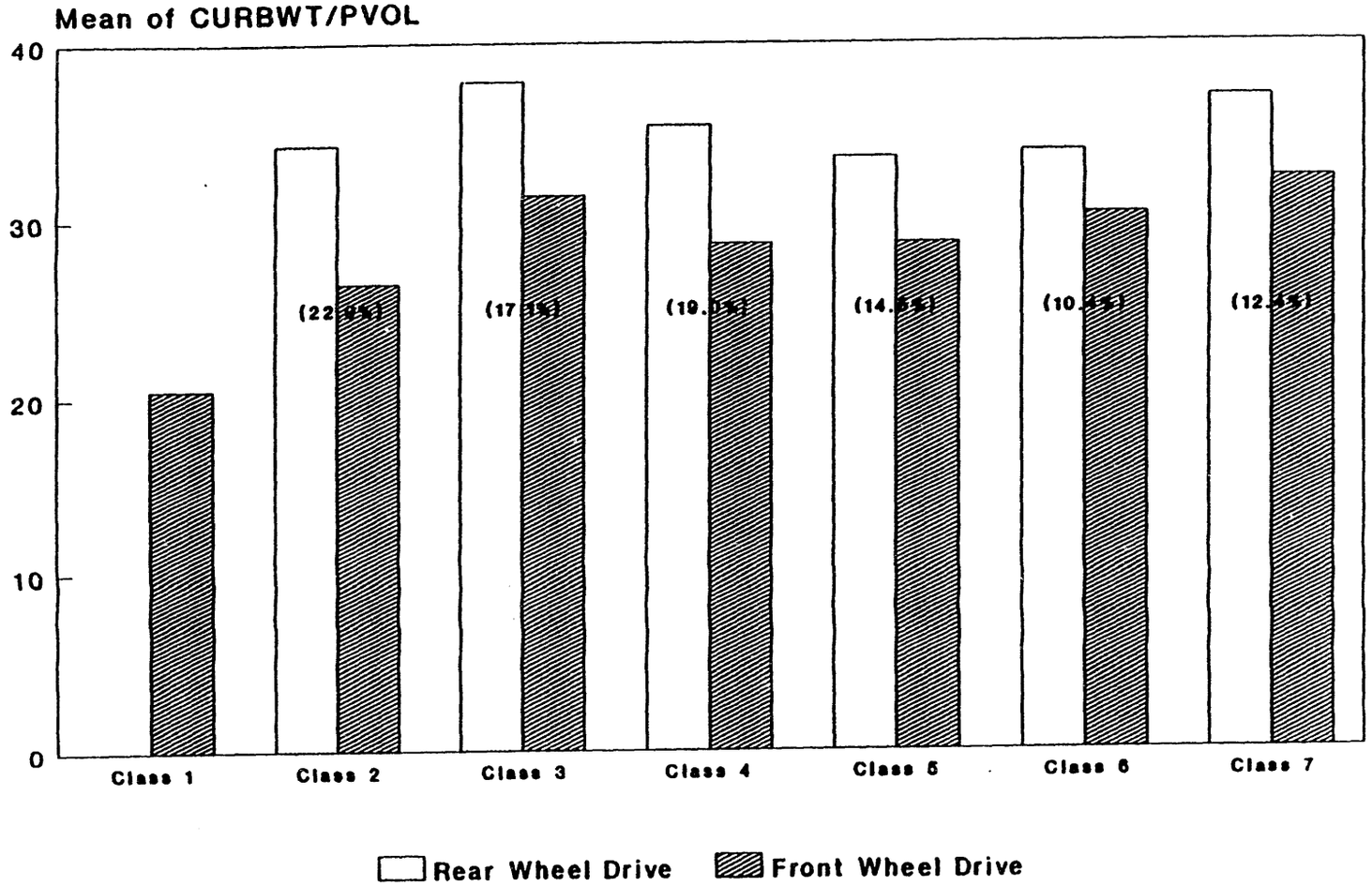
EEA's analysis of front-wheel drive versus rear wheel drive compares the benefits at equal interior volume. Two factors affect fuel economy - the increased drivetrain efficiency, and the weight reduction through improved packaging of the car.

DOT had extensively investigated the improvements of drivetrain efficiency between RWD and FWD designs in the late 1970's and early 1980's. They concluded that the reduced drivetrain losses in the FWD design would lead to a 1.5 percent improvement in fuel from this factor alone.

The weight reduction afforded by FWD designs over RWD can be gauged by several methods. The weight of the drive shaft, rear differential and rear axle weigh 150 to 160 lbs, which is the minimum weight reduction that can be expected, partially offset by the transaxle which weight 30-50 lbs in FWD vehicles. (Transmission weights are also slightly lower for FWD vehicles). The minimum net weight reduction of 100-120 lbs is not representative, as the packaging benefits are more significant.

One method to estimate the total weight reduction from FWD is simply to observe the weight/volume ratios for the current 1988 fleet. Since RWD is used in few cars, simple fleet averages would be unrepresentative. Rather, the fleet is divided into "market" classes, where each market class consists of vehicles with similar interior volume, performance levels and price. (The last two variables separate market class from size class, as it allows recognition of sports and luxury vehicles). In general all of the vehicles in one market class are considered as substitutable choices for a consumer, and vehicle attributes show relatively small variances among models within a market class, with the exception of the luxury class. (Luxury class is simply defined as all cars costing over $25,000 in 1988, and incorporates a wide variety of models.) Figure 3-1 shows the WT/VOL comparison. In virtually

Packaging Efficiencies Between RWD and FWD As Measured By CURBWT/PVOL



PVOL - Passenger Volume
CURBWT - Curb Weight
Percent Difference (RWD-FWD/RWD) in ()

FIGURE 3-1

every case the weight of an FWD vehicle is 10.5 to 19 percent lower at the same interior volume. No value for subcompact and minicompact cars is shown since all cars in these classes were already FWD in 1988.

The domestic manufacturers had only a handful of RWD models in 1988, and some of these have been replaced by FWD models by 1991. Table 3-1 shows the weight reduction available by comparing it with the actual replacement model weight or the weight of a similar competing vehicle of near equal volume and performance. The analysis is dependent to some degree on the comparison, especially for the sports cars. However, EEA does not anticipate that the Camaro/Firebird and Mustang will be converted to FWD. For all other RWD vehicles, we have utilized a mean value of 13 percent weight reduction. Some of this gain is due to the conversion from body-on-chassis type structure to unit body construction. The 13 percent weight reduction potential translates to a 8.5 percent improvement in fuel economy. The total benefit of FWD conversion for both weight reduction and driveline efficiency improvement is estimated at 10 percent. This <u>includes</u> the effect of conversion to unit body construction.

3.3 MATERIAL SUBSTITUTION

Material use in domestic cars changed sharply in the late 1970's and early 1980's, and material substitution was launched with the new Chevrolet Impala/Caprice for model year 1977. Relative to previous cars, the weight of the Chevrolet was lower by 600 to 700 lbs, while interior room was largely unchanged. On average, the fleet average weight decreased by over 500 lbs in the 1976 to 1984 timeframe. Since 1984, the pace of material substitution has slowed significantly. In fact, the 1977 Chevrolet was sold through model year 1990 with only cosmetic updates and very minor changes to material content. Table 3-2 shows the progression of material use in domestic cars during the 1976-1988 period. Between 1988 and 1990 weights of some cars have actually climbed, due to less weight conscious design.

TABLE 3-1

WEIGHT REDUCTION THROUGH FWD CONVERSION

1988 RWD Model	Body Type	Weight	Comparable FWD Model	Weight	Savings (%)
GM					
Chevrolet Caprice	Chassiss	3803	Olds 88	3296	10.8
Cadillac Brougham	Chassiss	4282	N/A	--	15.1*
Camaro/Firebird	Unibody	3357	Probe Turbo	2990	11.0
Monte Carlo	Chassiss	3270	'89 Regal/Supreme	2953	9.7
Ford					
Crown Vic/Gd. Marquis	Chassis	3780	Olds 98	3330	12.0
Thunderbird/Cougar	Unibody	3215	'89 Regal/Supreme	2953	8.2
Mustang V-8	Unibody	3190	Probe Turbo	2990	6.3
Chrysler					
Fifth Avenue	Chassis	3760	'90 Fifth Avenue	3215	14.5

* Estimated from similar vehicle volume/wt ratio for Cadillac FWD.

TABLE 3-2

WEIGHT REDUCTION THROUGH MATERIAL SUBSTITUTION

	Base*	HSLA	Plastics	Aluminum	GRP
Small Car	2150	1821 (15%)	1794 (16.5)	1561 (28.5)	1467 (31.8)
Compact Car	2600	2310 (14.4)	2265 (12.9)	2040 (22.5)	1870 (28.1)
Large Car	3586	3022 (15.3)	2979 (16.9)	2781 (22.5)	2429 (32.3)

* Baseline
Small car: Ford Escort
Compact car: Chevrolet Citation
Large car: Chevrolet Impala/Caprice

Source: SAE Paper 800803

In the near term, competition between plastics and HSLA will be intense, and cost considerations will dictate the specific winner in the absence of regulatory forces. According to Dr. Peter Beardmore[1], most plastic composites are more expensive than steel in high volume applications, but can be competitive in low volume specialty applications. The situation is changing rapidly as plastic structural component manufacturing technology and the materials evolve to become more manufacturable and meet consistency requirements. In 1989, few plastics for exterior panels were in use in the car market with the sole exception of the Chevrolet Corvette. Typically, plastics are currently being used in limited applications such as front fascias and spoilers, with fender applications only in the Cadillac. Of course, plastics are widely used for interior applications such as the dashboard and door moldings. Plastic components are not yet used for any structural (load bearing) parts.

Material substitution is likely to accelerate in pace in the post-1991 timeframe. The major materials considered for substitution are:

- High strength low alloy steel (HSLA)
- Reinforced Injection Molded (RIM) Plastic Components
- Sheet-Molding Compound (SMC) for body panels with Glass Fiber Reinforced Plastic
- Aluminum
- Graphite Fiber Reinforced Plastics (GRP)
- Advanced Composites

Other materials such as zinc and magnesium also will be used, but in lesser quantities. Costs associated with these materials vary by the particular requirement for the component, e.g., stiffness, bending strength, formability. In general, HSLA is the lowest cost increment and is compatible with tooling equipment used for plain carbon steel. Plastics (RIM and SMC) also are fairly low in cost but require new manufacturing and finishing techniques. Aluminum represents a fairly high cost option but also is capable of producing large

reductions in weight. GRP and advanced composites represent the highest cost option and produce the greatest weight savings.

DOT and GM had published some detailed studies in the early 1980's on the weight benefits and costs of using increased amounts of plastics and high-strength low alloy steels in the designs. The studies are still relevant largely because of the pace of material substitution slowed in the mid and late 1980's. The price of glass-fiber SMC has dropped since the time these papers were completed from $1.20/lb to $0.80 - 0.90/lb in 1990, while sheet steel prices have climbed by 15 to 20 percent in absolute terms over the same period.

GM researchers[2/] found that, at $1.20/lb, the cost per pound saved using SMC body panels over a range of applications, was $0.30/lb saved. They also found a very similar cost penalty for aluminum. In recent times, the cost of penalty of glass SMC designs have ranged from near zero to $0.20/lb saved, while aluminum has increased to $0.40/lb saved. (These figures were derived by scaling the GM estimates based on 1989/90 prices for materials). The fact that SMC is being used in some vehicles is proof of its cost-effectiveness.

The Department of Transportation (DOT) has performed detailed studies[2] of weight reductions possible in 3 different size classes of cars for four cases--HSLA dominant, Reinforced Plastics dominant, Aluminum dominant, and GRP dominant. The resulting weight reductions are detailed in Table 3-2. Although no one case will be representative of any manufacturer's strategy, EEA believes that the lowest cost materials will be used first in the 1990-2000 timeframe. This indicates that the most likely weight range will like near those predicted for the HSLA and Reinforced Plastics cases. In the post-2000 period, Aluminum and GRP may be used in specific components if the costs can be justified in fuel savings. Researchers from ALCOA[6/] found even large wight reduction potential with aluminum. They reported that an X-body car could have weight reduced from its 2700 lbs (in 1982) to 1550 lbs with an aluminum intensive design.

The DOT weight savings estimates includes all of the secondary weight benefits associated with material substitution. For example, as the weight of the body structure is reduced, a smaller engine is required, and the suspension and tires can be reduced in weight also. The DOT study used historical data to compute secondary weight reductions[3], but many feel that their estimates are too optimistic to be realized in production as it does not account for the need to maintain ride quality, or the inability of drivetrain engineers to adjust drivetrain parameters to account for all primary weight changes. Table 8-2 indicates that a 15 percent weight reduction is possible in the near term, but the industry consensus appears to be closer to 10 percent. VW[4] has published estimates for their Golf vehicle (which is representative of most modern FWD subcompact/compact cars) and concluded that a 10 percent weight reduction was both possible and likely by 2000. Another confirmation comes from the Automotive Material Conference held in December 1989 where Donald Smith, professor at the University of Michigan and a panel composed of specialists in the industry projected[5] weight reduction potential in excess of 225 lb through material substitution. William Risk, president of Autopolymer Design Inc. reported that existing product programs would increase plastics use from 220 lb in 1988 to 360 lbs by the mid-1990's. In contrast, the ALCOA[6] study seems to indicate reductions to levels not supported by other work.

More recently, detailed analysis for the potential for weight reduction using aluminum in select parts was provided by Mazda.[7] The analysis classified aluminum substitution into 4 categories.

- Parts common to all models
- Parts used in some specific models
- Parts in limited sports models
- Potential future use of aluminum

The analysis was done for the Mazda Familia (Protoge in U.S.) with a 1.5 L engine. The base model weights 2100 lbs curb weight (950 kg). As shown in Table 3-3, weight reduction from parts in the first three categories was

TABLE 3-3

WEIGHT REDUCTION POTENTIAL

FOR MAZDA FAMILIA THROUGH ALUMINUM USE

• Common Parts for All Models	Wt. Reduction (kg)
4 pistons	0.3
Cylinder head	7.2
Intake manifold	2.2
8-rocker arms	0.38
Timing chain cover	0.9
Oil, fuel, water pump	2.05
EGR/Lead valve	0.35
Alternator/starter body	1.0
Transmission Case/Clutch housing	7.1
Miscellaneous	0.52
Steering gear housing	0.5
Wiper motor/arm	0.45
Cylinder head cover	1.50
2 wheel brake cylinders	0.10
Total	26.57
• Parts used in specific models	
Radiator	1.2
Cylinder block	14.0
Crank Shaft	5.0
4 Wheels	22.4
Shift fork	0.3
Brake master cylinder	0.6
Engine mount	0.5
	44.0

TABLE 3-3

WEIGHT REDUCTION POTENTIAL

FOR MAZDA FAMILIA THROUGH ALUMINUM

(Continued)

- Parts for use in limited sports models

Clutch pedal	0.35
Disc caliper	3.50
Lower suspension arm (x2)	2.80
Hood	8.0
Brake pedal	0.5
Jack/spare wheel	5.5
Grill	0.4
Disc brake covers	0.4
Valve springs	0.05
Heat insulator	1.5
Total	23.4

- Potential for future use

Suspension lateral links, rear	1.3
lateral links, front	1.3
trailing links	1.8
Steering knuckles	3.5
Engine mount member	5.0
cross member	6.0
Fenders (x2)	8.0
Total	26.9

estimated to be 94 kg, approximately 10 percent of total car weight. Other than weight reduction the use of aluminum serves other function. It's use in pistons, cylinder head and intake manifold improves thermal conductivity, reducing octane requirements. It can serve a decorative purpose, when used for wheels or cylinder head covers. Its use in castings such as the transmission case improves productivity. Hence, a cost for weight reduction alone understates the cost-effectiveness of aluminum.

Hence, EEA has projected a 10 percent weight reduction potential for all cars in the 1990-2001 timeframe, equivalent to an average weight reduction of close to 300 lbs.

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4. IMPROVEMENTS IN AERODYNAMICS

4.1 ENGINEERING DESCRIPTION

Aerodynamic drag is a resistance force on a moving car's surface areas caused by wind intensity and direction. Aerodynamic drag is a function of a car's frontal area and body shape. The drag coefficient is a measure of the streamlining of the car body. The higher the coefficient, the greater the drag; the larger a car's frontal area, the higher the drag. Drag-related power requirements are a cubic function of a car's speed through the air. Drag has a minimal effect at low speeds and a strong impact at high speeds, so that reduction in drag affects highway fuel economy much more than city fuel economy.

Aerodynamic drag cannot be reduced without affecting the styling characteristics of the automobile. Since drag depends on body shape and frontal area, a change in drag characteristics can impact the vehicle's interior volume and its utility to the consumer. For example the drag force could be significantly reduced by narrowing the car width to accommodate two people per seat instead of three. However, this would affect the car's carrying capacity. Streamlining of the vehicle's shape is subject to these limitations, as well as public acceptance of highly aerodynamic shapes.

Since aerodynamic drag is so inextricably related to vehicle design, it is not feasible to distinguish the application of improved aerodynamics from styling in current vehicles. There is no question that greater attention is being paid to the vehicle's drag coefficient, but this has always been compromised by styling requirements as discussed below.

The measured of drag co-efficient can be influenced by the measurement as well as is the design of the wind tunnel itself, and some researchers believe that automanufacturer claims for several models may be based on different

measurement methods. Nevertheless, the only sources of data on vehicle drag co-efficients (or C_D) are from the manufacturers themselves. Table 4-1 shows the drag co-efficients of several domestic used imported cars in 1988. Data on the CD of some vehicles especially those with high drag co-efficients) are unavailable. From publicly available data on most cars, in combination with some unofficial estimates for vehicles where data is unavailable, EEA estimates that the average C_D in 1988 was in the 0.37 - 0.39 range.

4.2 DRAG REDUCTION POTENTIAL

Since 1986, several vehicles with low drag co-efficients have been introduced. The first aerodynamic U.S. domestic car was Ford's Taurus/Sable with drag coefficients of 0.33, and several other cars have followed suit. GM's Olds Cutlass Supreme for 1989 boasts a C_D of below 0.30, and some recent (1990) GM models have C_D values in the 0.31 range. The most aerodynamic cars sold in the U.S. in 1990 are the Lexus LS400 and the Subaru XT. In Europe, the most aerodynamic car sold in the Opel Calibra with a C_D of 0.26.

Analysis of product plans of the manufacturers show that most new models will emphasize aerodynamics, while some luxury vehicles may still retain the "formal" look that leads to high C_D. Nevertheless, by 1995, it appears that the average C_D will be 0.33 - 0.34 corresponding to a 10 percent reduction in drag with reference to the 1988 average. (Some models like the Taurus will see no reduction at all, while other like the Crown Victoria will experience a 20-25 percent reduction). Given that there are some cars already available with drag coefficients of 0.29, it appears reasonable to project that the 2001 fleet average will be 10 percent lower than 1995's with a C_D of 0.29 ~ 0.30. These levels of drag reduction are not expected to alter vehicle attributes significantly.[1] No reduction in frontal area is forecast for either time-frame, in keeping with the analytical requirements of constant interior volume.

It should be noted that the reduction of drag co-efficient <u>must</u> be accompanied by other changes to match the drivetrain to the reduced horsepower demand. If

TABLE 4-1

DRAG CO-EFFICIENTS FOR SELECTED 1988 VEHICLES

DOMESTIC CARS

Make	Best Model	Cd	Frontal Area (sq. ft.)	Worst Model	Cd	Frontal Area (sq. ft.)
AMC/Renault	Medallion 4-dr.	0.34	21.2	Alliance 4-dr.	0.39	20.5
Chrysler	LeBaron Coupe	0.35	20.8	Fifth Avenue	0.48	23.7
Plymouth	N.A.	N.A.	N.A.	Horizon	0.42	20.3
Dodge	Daytona Shelby Z	0.35	20.7	Omni	0.42	20.3
Ford	Taurus	0.33	22.7	Crown Victoria	0.50	24.4
Lincoln-Mercury	Sable	0.32	22.7	Grand Marquis	0.50	24.4
Buick	Riviera	0.37	22.3	Regal	0.46	24.5
Cadillac	Allante*	0.34	22.3	Brougham	0.46	24.5
Chevrolet	Camaro Z-28	0.33	21.4	Caprice	0.45	24.8
Oldsmobile	Calais 2-dr.	0.37	20.7	Customer Cruiser Wagon	0.45	27.4
Pontiac	Trans-Am**	0.35	21.4	Safari Station Wagon	0.45	27.4

NOTES: * With hardtop ** With aero package.

IMPORT CARS

Acura	Legend	0.32	21.85	Integra	0.34	20.0
Alfa Romeo	Milano	0.37	20.0	Spider	0.40	18.0
Audi	5000S	0.32	22.0	4000CS Quattro	0.42	20.8
Austin Rover	Sterling	0.33	21.2	N.A.	N.A.	N.A.

TABLE 4-1 (Continued)

DRAG CO-EFFICIENTS FOR SELECTED 1988 VEHICLES

IMPORT CARS

Make	Best Model	Cd	Frontal Area (sq. ft.)	Worst Model	Cd	Frontal Area (sq. ft.)
BMW	735i	0.32	N.A.	N.A.	N.A.	N.A.
Honda	CRX Accord Sedan	0.32	18.5 20.5	Civic Sedan, Wagon 4wd Wagon	0.39	20.1* 21.9*
Hyundai	Excel	0.36	N.A.	--	--	--
Jaguar	XJ-6	0.37	21.3	XJ-S Cabriolet	0.41	20.1
Mazda	RX-7	0.29	N.A.	323 Sedan	0.38	N.A.
Mercedes-Benz	260 & 300E	0.31	22.4	560SL	0.43	20.2
Mitsubishi	Cordia	0.33	18.7	Mirage 2-dr.	0.39	19.2
Nissan	300-ZX	0.31	19.6	Maxima Wagon	0.39	20.1
Porsche	924S, 944 Turbo	0.33	N.A.	911 Carerra Turbo, 928S	0.39	N.A.
Saab	9000	0.34	22.0	900	0.41	21.0
Subaru	XT Coupe	0.29	19.7	Station Wagon	0.38	20.6
Toyota	Celica GT-S	0.34	19.0	Van	0.39	N.A.
Volkswagen	Golf GT, GTI, Jetta	0.36	20.4	Cabriolet, Fox	0.46	19.7
Volvo	760 GLE**	0.37	23.1	--	--	--

NOTES: * Depending on model ** 1983 European model

This chart lists each auto manufacturer's most aerodynamic and least aerodynamic models, their coefficients of drag (Cd) and frontal areas. All figures are based on manufacturers' claims. In some cases, vehicle frontal areas are not available (N.A.)

SOURCE: Automotive News.

only the drag co-efficient is changed, the load on the engine is reduced. While overall fuel consumption will be reduced, operating at a lower load factor will increase bsfc.[2] To compensate, the engine speed must be reduced by reducing the N/V ratio in top gear. As a result, the engine RPM is lowered so that the new operating point has at least the bsfc of the original pre drag reduction operating point. It is also possible to actually improve the bsfc since at the same speed, the engine will be running at lower RPM, decreasing frictional loss. This effect is captured in EEA's analysis as the overdrive gear effect (please see section 7).

The cost of aerodynamic improvements are associated primarily with the expenses related to research the body styling and trim details to lower the drag coefficient. The essential inseparability of aerodynamic drag co-efficients and styling requirements make it difficult to allocate precise "costs" to drag reduction. At C_D levels of 0.33-0.34, there are no significant variable costs associated with drag reduction. At lower levels of C_D (in the 0.30 range), manufacturing costs increase because of the need to maintain better tolerances for body parts and improved fit and finish quality. (The use of a covered underbody is not expected to be necessary to meet the 0.29-0.30 target). Flush windows also impose some variable cost penalties. However, these quality of fit-and-finish improvements are also required to be competitive in the current marketplace, so that it is difficult to allocate costs to aerodynamic drag reduction alone.

REFERENCES FOR SECTION 4

1. Buchheim, R., et al., "The Control of Aerodynamic Parameters Influencing Vehicle Dynamics," SAE Paper No. 850279.

2. Jansen, L.H. and Emmelmann, H.J., "Aerodynamic Improvements - A Great Potential for Better Fuel Economy," SAE Paper 780267.

5. TIRES, LUBRICANTS AND ACCESSORIES

Small gains in fuel economy can be attributed to:

- Decreases in the rolling resistance coefficients of tires
- Decreased viscous and frictional losses due to the use of advanced lubricants
- Reductions in power losses in accessory drives.

5.1 TIRES

The use of radial tires has spread across the entire new car fleet. However, radial tires of more advanced designs manufactured from rubber compounds with lower hysterisis losses can reduce the rolling resistance of all tires. In a study reported in 1981, researchers from the EPA[1] found that fiberglass belted tires had 5 percent lower rolling resistance than steel belted tires, and that "all season" treads have 5.6% higher rolling resistance than conventional treads. Studies on tire inflation pressure by B.F. Goodrich[2] showed that rolling resistance continues to decrease to inflation pressures of up to 40 psi, but is not affected above that pressure. However, it is also well known that tire performance is a complex function of design variables, and that handling characteristics and traction and often adversely affected by the design factors that decrease rolling resistance.[3]

No detailed data on current tire rolling resistance coefficients (C_R) are available publicly, but tire companies suggest that the average C_R is around 0.012. In recent years, there has been a tread towards high performance tires of low aspect ratio, that have had impacted rolling resistance unfavorably for fuel economy. However, EEA contacts with tire companies' staff[4] indicate that rolling resistance will decline by 10 percent over the next decade on a "same tire" basis but the trend towards higher performance tires will negate half the benefit. Hence, a total of reduction of 5 percent in rolling resistance is forecast over the next decade through:

- improved tread and shoulder design
- use of different high performance belt materials, such as aramid fiber
- improved rubber compounds

Tire industry publications and material suppliers have provided data on potential changes possible to rolling resistance while maintaining handling and traction properties. DuPont[5] has performed studies on aramid yarn tire reinforcements (belts). Aramid fibers have much higher specific strength in comparison to steel or glass. Tests have shown aramid reinforced tires' rolling resistance was 9 percent less than steel belted tires. Aramide yarn for belt material can also save 4 to 5 lbs of weight per tire.

More recently, Goodyear[6] introduced a new tire called the Invicta GFE, a steel belted tire with new polymer-rubber components. Goodyear has claimed 20 percent lower rolling resistance for the Invicta GFE over "comparable aftermarket tires" although no specifics were provided in publicly available data on the exact nature of the comparison. The fuel economy impact was estimated at 4 percent, consistent with the 20 percent rolling resistance reduction estimate.

5.2 LUBRICANTS

Synthetic axle and engine lubricants have been available for several years,[7] but have not found wide acceptance because of the substantial cost premium for small fuel economy benefits.[8] It is unlikely that the situation will change over the next decade, and their benefits are not likely to be seen in the fleet. However, 5W-30 oil has recently come into use in some U.S. vehicles as a factory fill oil, and automanufacturer submissions to DOT have claimed a 0.5 percent fuel economy benefit, on average, by replacing 10W-30 with 5W-30 oil. There may be other small benefits associated with improved axle and differential lubricants, but these benefits may be only in the 0.1 to 0.2 percent range.

5.3 ACCESSORIES

Accessory drives absorb power from the engine and their influence is inversely related to engine size. In cars, the cooling fan, water pump, alternator, power steering pump, and air conditioner (when used) can account for a major (15 percent) penalty in fuel consumption. Efficiency improvements in all of these accessories and conversion to thermostatically operated electronic cooling fans can provide up to a 3 percent improvements in fuel economy. All of these improvements have been already incorporated during the 1980-1990 time period.

An additional 0.5 percent improvement in fuel economy is possible through redesign of the drives and improvements in fan blades coupled with reduced heat rejection from the engine (which may be necessary for meeting exhaust emissions standards). These improvements will be phased in during the 1990-2000 period. Costs for such improvements (except the electric fan) are small, typically amounting to about $10.00 per vehicle.

The variable speed accessory drive has been researched extensively by DOE.[9] However, their cost-effectiveness is poor if the vehicle features an electric fan as all FWD vehicles do. Ford was ready to introduce such a drive in the mid-1980's but canceled the introduction due to durability problems, and difficulty in matching the alternator load requirements under some conditions. As a result, EEA does not foresee the use of these devices in the next decade.

The power steering pump absorbs a significant fraction of accessory energy, especially at low speeds. An electric power steering system has been developed and recently commercialized. Due to electrical power requirements, it may be best suited for small cars. The electric power steering system has been recently displayed in Japan, by Honda.

Honda researchers[10] provided data on the NSX sports car equipped with an electric power steering. The system was tested on the Japanese test cycle as well as the U.S. cycle, and displayed fuel economy benefits (see Table 5-1) is

TABLE 5-1

COMPARISON OF ELECTRIC TO HYDRAULIC

POWER STEERING ON ACURA NSX

Test Cycle	Electric	Hydraulic	% FE Benefit
10-mode	7.32 km/l	7.14 km/l	2.52
60 km/hr	14.48 km/l	14.17 km/l	2.19
LA-4	20.51 MPG	20.01 MPG	2.50
Highway	28.88 MPG	28.17 MPG	2.52

Source: JSAE Paper No. 91102.

the 2.2 to 2.5% over all cycles. Honda suggested that the benefits were even larger on small cars where the power steering pump absorbed a greater fraction of total output. Other manufacturers contests these large values, although no data is available. EEA has selected 2 percent benefit is a compromise in the absence of other information.

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1. Thompson, G.D. and Reineman, E.N., "Tire Rolling Resistance and Vehicle Fuel Consumption," SAE Paper No. 810168, February 1981.

2. Collier, B.L. and Warchol, J.T., "The Effect of Infection Pressure on Bias-Belted and Radial Tire Performance" SAE Paper 800087, February 1980.

3. Steve Walter, "The Effects of Five Basic Design and Construction Parameters a Radial Tire Rolling Resistance and Cornering Force" SAE Paper 830160, February 1983.

4. Private communication with Goodyear and Dunlop, 1990.

5. Automotive Engineering "Aramid Reinforced Tires" Vol 99 Number 8, pg 23, August 1990.

6. Goodyear News Release, Akron, Ohio, July 22, 1990.

7. Lohuis, J.R., "The Performance of Fuel Saving Engine Oils," SAE Paper No. 800436, 1980.

8. Wards Engine Update, "1-year, 25,000 mile Synthetic Oil Touted by Mobil," May 15, 1985.

9. Garett, "Constant Speed Accessory Drives" Contractor Report to the DOE, Presented at Highway Vehicle Systems Contractor Coordination Meeting, October 1981.

10. Japan AutoTech Report "Honda Interested in Expanding Use of Electric Power Steering" pg. 17, Vol 124, 1991.

6. SPARK IGNITION ENGINE TECHNOLOGY

6.1 OVERVIEW

The spark ignition (SI) piston engine is expected to be the dominant form of motive power in the next decade. Although the S.I. engine has been in existence for a 100 years, steady and continuous improvements are being made. As noted in Section 2, the areas where technical improvements are possible can be grouped into:

- Increased thermodynamic efficiency
- Decreased pumping loss
- Decreased mechanical friction loss

Any new type of engine incorporates improvements in all three areas. We have discussed specific engine types and specific component changes that may cause improvements in any or all of the three areas.

Prior to 1980, Ford was the only manufacturer that offered even one overhead cam engine among the domestics, and all other domestically manufactured engines were of the overhead valve (OHV) type. All domestic pre-1980 engines were carburetted with the sole exception of the Cadillac 350 CID V-8 offered in the Eldorado and Seville. OHV engines still continue to dominate the domestic car fleet in 1988, although most engines are now fuel injected. As a reference, the 1988 carburetted OHV engine serves as a baseline for comparison of OHC and 4-valve engines. Detailed data on the few remaining engines of this type showed that they typically produced 32-35 BHP/litre, and 67-70 N-m/litre of torque. The categories of engines now in the marketplace are as follows.

Advanced OHV Engines are a recent phenomenon as domestic car manufacturers have updated older engines with new "fast-burn" heads, improved piston and ring designs, better manufacturing tolerances of the cylinder bore, noise

reduction and improved airflow. The engine block retains the same basic dimensions of the older OHV designs. Such engines have outputs of 42-45 BHP/litre and torque ratings of 74-76 N-m/litre.

Overhead Cam Engines of older designs are roughly equivalents in specific output and specific torque to the advanced pushrod engines. These older designs are represented by the Chrysler 2.2/2.5 litre 4 cylinder engines designed 10 years ago and the Ford 2.3L that dates from the early 1970's but has been updated since. More modern OHC engine have specific outputs of 50-54 HP/L and torque of 80-82 N-m/L. High performance OHC engines have increased specific outputs of 60-63 BHP/L with only slight reduction in torque. However, both the torque peak and HP peak are realized at much higher RPM.

4-valve engines are only of the overhead cam type, some featuring single overhead cam (SOHC) while others have double overhead cams (DOHC). The four valves permit improved breathing and a more compact combustion chamber with a central spark plug that allows for higher compression ratios (CR). Typically 4-valve engines can have a CR of 10.0 without being knock limited while most OHV/OHC engines have CR's of 8.8 to 9.2. The specific output of a modern 4-valve engine optimized for fuel economy is 60 to 65 BHP/L with torque of 88-90 N-m/l. If optimized for high end performance, the maximum torque decreases only slightly but maximum output increases to 75-80 BHP/L, with peak torque RPM and peak horsepower RPM increasing significantly. A summary of engine classifications is provided in Table 6-1.

Fuel injection can also improve the specific output of engines. The simpler throttle-body (or single-point) injection provides only modest gains in specific output as it does not allow a redesign of the intake manifold to maximize airflow. Multi-point fuel injection offers the benefit of being adaptable to tuned intake manifolds and more accurate fuel delivery that is matched to requirements of the engine during transients. Throttle-body and multipoint fuel injection are widely used in the 1988 fleet, and carburetors

TABLE 6-1

ENGINE CLASSIFICATION

Class	Valves/cyl	Specific Power (HP/L)	Specific Torque (N-m/L)	Examples
OHV (old design)	2	30-35	67-70	Ford 302 V-8
Advanced OHV and OHC	2	44-46	74-76	Ford 181V-6 GM 3300/3800 V-6
Modern OHC	2	50-54	80-82	Most Japanese engines
Modern OHC (High performance)	2	58-60	78-80	Mercedes 3 litre, BMW 3.5 litre I-6
Modern 4-valve	4	62-65	90-92	GM Quad-4
Modern 4-valve (High performance)	4	70-75	88-90	Ford/Yamaha 3L V-6

were restricted to just one engine family for Chrysler and GM (in the 318 V-8 and the 307 V-8 respectively) in 1988. All Ford engines were fuel injected.

Variable Valve Timing can provide reduction of pumping loss by closing the intake and potentially, the exhaust valves, depending on the speed and load. Valve timing is known to have favorable effects on engine output across the RPM range, because the current system of fixed valve timing is largely a compromise for the range of load and speed conditions encountered. The problem has always been the lack of good mechanisms to vary valve timing. Most schemes have proved unreliable mechanically and/or caused such large increases in mechanical friction that the pumping loss benefits were overwhelmed. More recently, a simple mechanism suitable for DOHC engines that changes the timing of intake valves, but not lift or duration has been commercialized by Nissan and Mercedes. In 1990, Honda introduced a more sophisticated system that varies timing, lift and duration between two fixed sets of values, one for low speed and the other for high speed.

Engine mechanical friction reduction is an ongoing effort and evolutionary improvements in friction are being realized constantly. The level of friction in an engine is characterized in normalized terms as friction mean effective pressure (fmep). A typical advanced OHV or OHC engine has a brake mean effective pressure at wide open throttle of 930 kPa (135 psi), while the fmep is 170 KPa. Major components contributing to friction are piston/rings, valvetrains, crankshaft/seals and oil pump, in order of importance. Considerable work has gone into designs of these components to reduce friction. Friction reduction is usually incorporated into modern engine designs.

The specific fuel economy benefits associated with engine design type and through fuel injection and friction reduction are documented below. The overhead valve engine is used as a comparison baseline.

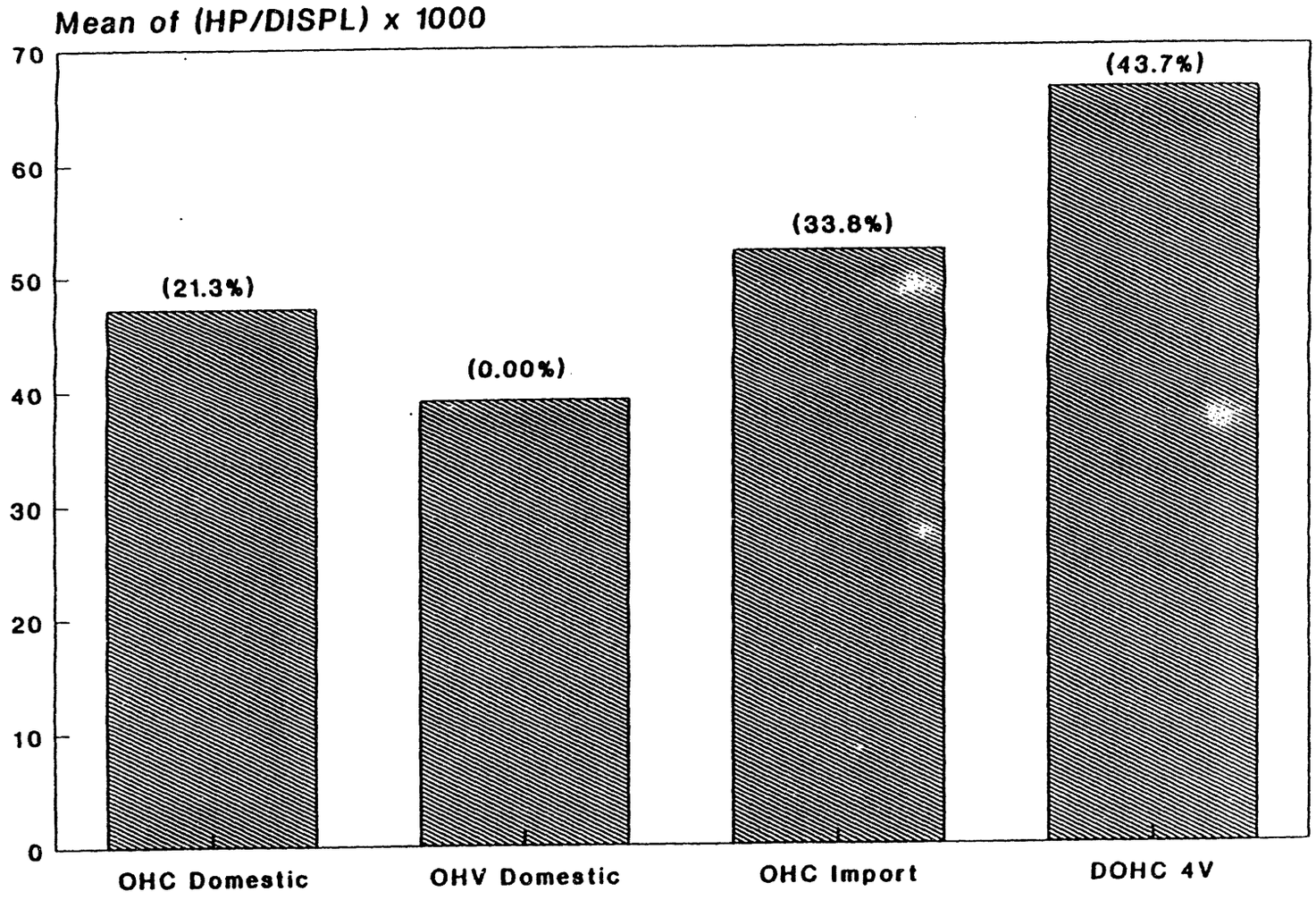
6.2 OVERHEAD CAM ENGINES

As noted, overhead cam engines can have valve timing adjusted to provide up to 60 BHP/L in high performance applications. In the more common application where fuel economy is important, discussions with manufacturers and current design practice suggest that 50-52 BHP/L is the optimal range. Figure 6-1 shows the actual 1988 averages for OHV, domestic OHC, import OHC and 4 valve engine specific outputs. The domestic OHV output figures aggregate the two sub-classes of advanced OHV and old OHV. If the import OHC average is used as a representative figure (since they are more modern designs than domestic OHC engines) for the specific output, it coincides with the general comments obtained from manufacturers. Figure 6-2 shows the specific torque ratings for 1988 engines. It appears that modern OHC designs offer an 7.9 percent benefit over the average OHV engines. The more appropriate comparison is against the advanced OHV engine, where the torque benefit is 6 percent.

In the EEA analysis of fuel economy potential, the case considered is an advanced OHV engine of 44 BHP/L being replaced with an OHC engine of 52 BHP/L output. Torque will increase 6.6 percent from 75 N-m/L to 80 N-m/L. To maintain constant performance, the OHC engine is assumed to be downsized by 8 to 10 percent. Peak horsepower will <u>increase</u> a 6 to 8 percent but peak torque will <u>decrease</u> by 2 to 4 percent and low end torque by 5 to 7 percent. In order to compensate for the low end torque loss, axle ratio must be increased by 5 percent. This maintains the same "launch feel" and top gear gradeability.

The OHC engine has a more rigid valve train, which allows reduced valve spring tension, as well as higher valve accelerations, relative to an OHV engine. This results in reduced engine friction, improved combustion and reduction in pumping loss. Ford[1/] has estimated the net benefits of OHC engines over OHV (2-valve) engines at constant displacement to be 1%. At constant performance, the net benefit is calculated by EEA as follows:

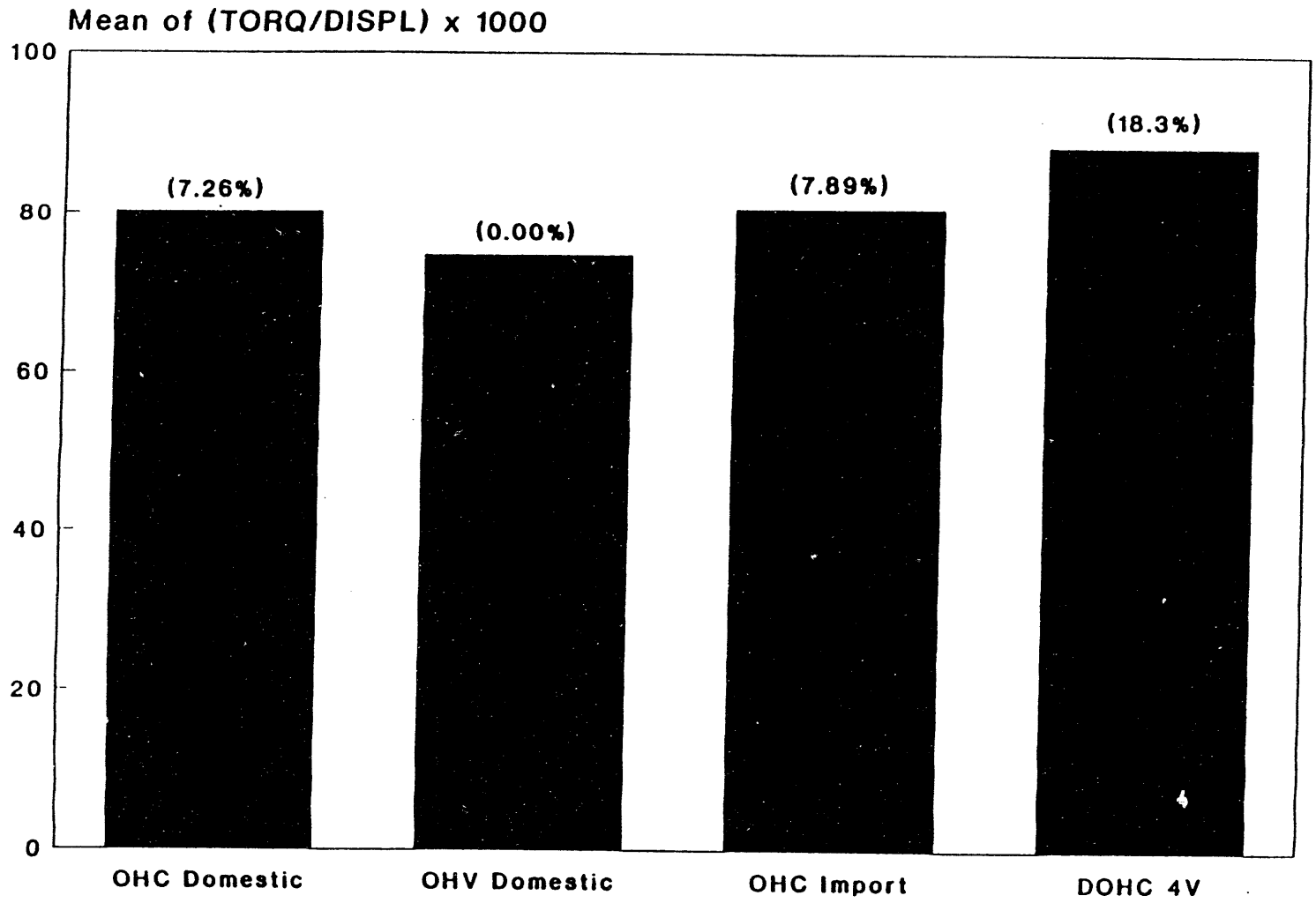
Differences in Means for OHC, OHV and DOHC 4 Valve Engines by Domestic and Import Classifications



Difference in () with OHV Dom. as base.

FIGURE 6-1

Differences in Means for OHC, OHV and DOHC 4 Valve Engines by Domestic and Import Classifications



Difference in () with OHV Dom. as base.

FIGURE 6-2

OHC to OHV benefit	+1%
8 to 10 percent CID reduction	+3.0 to +3.8%
5 to 7 percent axle ratio increase	-1.1 to -1.3%
Total benefit	+2.9 to +3.5%

Ford[1/] has used slightly different factors in their assessment of the effect of displacement decrease and axle ratio increase, but has arrived at a similar net benefits estimate of 3.5 percent.

6.3 4-VALVE ENGINES

The calculation of DOHC 4-valve engine benefit is similar conceptually to that of the OHC engine to OHV engine benefit calculation shown above. It can be shown from actual 1988 data that a 4-valve engine of modern design is capable of producing 90 N-m of torque per liter and 60 to 65 BHP per liter of specific output. These values represent a 10 percent increase in torque and a 20 percent increase in peak power over an OHC 2-valve design.

The 4-valve engine has other features that impact fuel economy. First, the increased number of valves (4 vs. 2) causes some increase in valve train friction. The friction is not doubled because each valve is much smaller and lighter, and the valve spring tension is lower. Second, the 4-valve engine allows a better combustion chamber design, with a central spark plug. For maximum fuel efficiency, Toyota[2/] has developed a compact combustion chamber with a narrow included angles between intake and exhaust valves. Higher performance designs sacrifice this feature to maximize airflow and feature a large included angle between intake and exhaust valves. Third, the central spark plug location and improved airflow characteristics allow the use of higher compression ratios. Many currently available 4-valve engines such as the GM Quad-4 and the Infiniti 2 liter already utilize a compression ratio of 10:1 which is one point higher than the ratios used in current OHC and OHV engines.

The constant performance comparison between OHC/2 valve and DOHC/4-valve requires that the 4-valve engine be 10 percent smaller than the 2-valve engine. Peak torque is constant while peak horsepower increases by 10 percent in this comparison. However, low-end torque (at 1500 RPM) is reduced in this comparison and axle ratio must be raised to preserve launch from rest. The components of the fuel economy benefit estimate are as follows:

10 percent CID decrease	+ 3.8%
5 percent axle ratio increase	- 1.1%
Increase thermodynamic efficiency	+ 2.5%
Increase valve-train friction	- 0.5%
Decreased aerodynamic friction	+ 0.5%
Net benefit	+ 5.2%

In submissions to the OTA, Toyota[3/] has suggested a 5.0 percent benefit for the 4-valve engine, consistent with the above estimate.

GM has provided[4/] a very detailed comparison between two engines of near equal performance, in this case the advanced OHV 2.8 litre V-6 rated at 130 HP and the DOHC 4-valve 2.3 L (Quad 4) engine. Both engines were offered in 1988 in the same car (Pontiac Grand Am) with the same transmission and axle ratio. Both engines also employed multipoint fuel injection, although the inlet manifold in the Quad 4 is more highly tuned. (Note that the EEA computations allow an increase in axle ratio to preserve low speed acceleration). In this case, the comparison is between a V-6 are a 4-cylinder engine which allows a further reduction in engine friction (see Section 6.4). The power and torque curves of the two engines are shown in Figure 6-3.

The 2.8L V-6 engine provided a fuel economy of 26.3 MPG composite while the Quad 4 was rated at 32.2 MPG composite, a total increase of 22.4 percent. The GM detailed analysis allowed a breakout of the individual contributions associated with displacement reduction, improved thermodynamic efficiency and reduced friction. GM's estimates are compared to the EEA standardized estimates below:

POWER COMPARISON

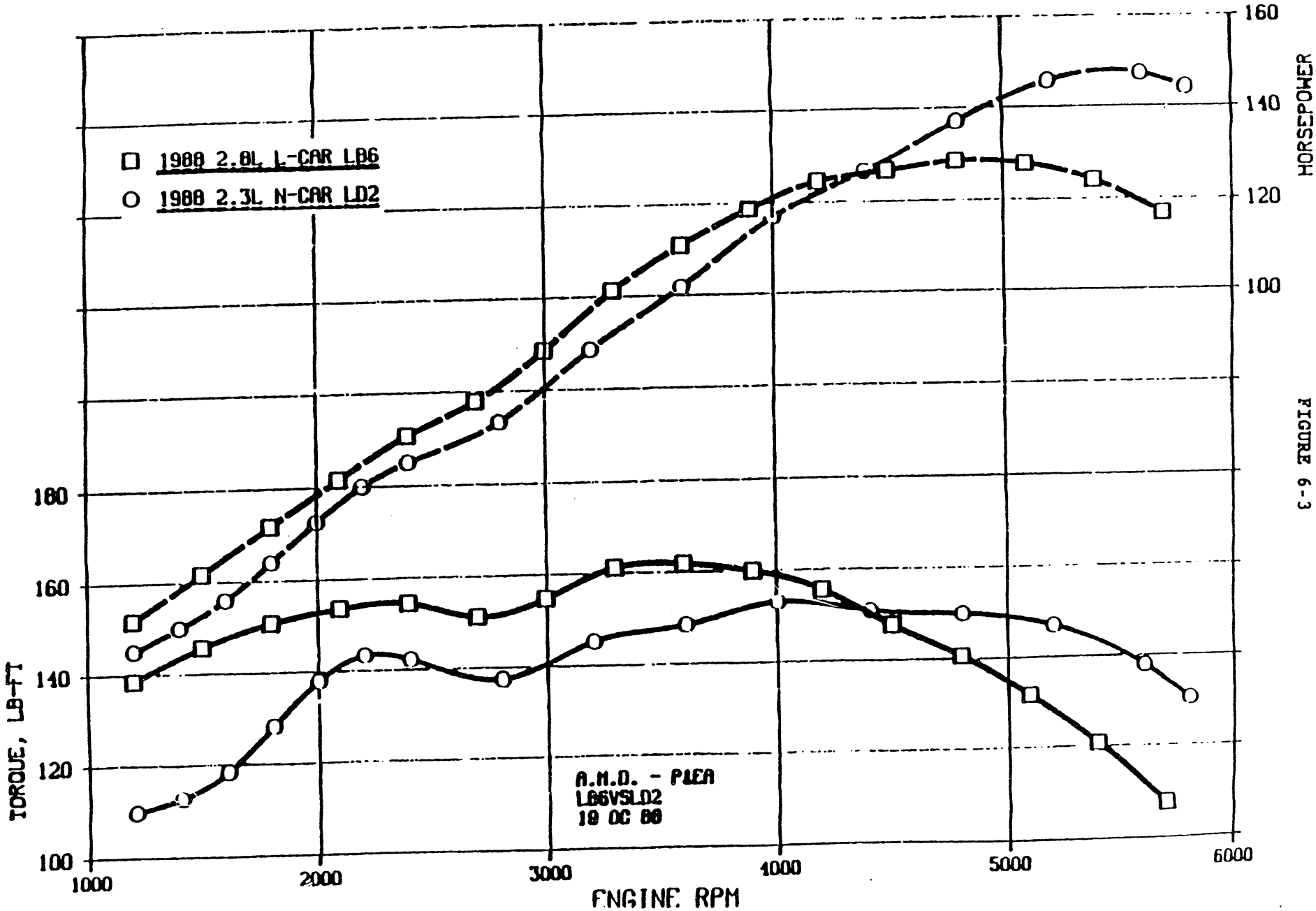


FIGURE 6-3

	GM Estimate F/E Benefit	EEA F/E Benefit
Displacement reduction	12.0%	7.6%
Compression Ratio	2.2%	2.5%
Compact Chamber Design	2.4%	
4 vs. 6 cylinder Friction	2.4%	3.0%
OHV vs. Pushrods	2.4%	1.0%
Other	0.8	3.0*
TOTAL	22.4	17.1

The EEA estimate agrees with GM's in the total friction benefit but appears to significantly understate the benefit of displacement reduction and combustion chamber design improvement. This may be partially due to the fact that 2.8L V-6 is not one of GM's most efficient designs, but it clearly shows that the EEA estimates are conservative. In addition, the EEA estimate allows for an axle ratio increase by 10 percent for the particular case examined by GM (5 percent for OHV to OHC/2V and another 5 percent for OHC/2V to OHC/4V), and it is noted that actual cars on sale do not necessarily follow this practice, as illustrated by GM's N-car. However, this is not a true constant performance comparison.

In EEA's comparison, the OHV 2.8L V-6 with a 2.84 axle and three speed automatic transmission can be replaced on OHC 2.5L V-6 with a 2.98 axle ratio, or DOHC 4-valve 2.3L engine with a 3.13 axle ratio. At 2000 RPM, it can be seen from Figure 6-3 that the Quad 4 provides 10 percent lower torque, which is exactly offset by the 10 percent axle increase ratio.

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* EEA's estimate of friction reduction from more modern design, plus the effect of tuned inlet manifold.

6.4 FUEL INJECTION

There are two types of fuel injection (FI) - single point (or throttle-body) injection (SPI) and multipoint fuel injection (MPI). SPI is used in all naturally aspirated 4-cylinder engines made by GM and Chrysler, as well as in a few low cost Japanese models and the Ford Escort in 1988. Most other vehicles use MPI. Carburetors are used in entry level Japanese models and Korean models in 1988, as well as in 2 old design V-8 engines among the domestic models.

The benefit of SPI over the carburetor has been documented in several submissions by the manufacturers to DOT in the early 1980's. A significant part of the gain in fuel economy is associated with the ability to eliminate the air pump required by carbureted vehicles to meet the emission standards. The air pump absorbs power from the engine and rais exhaust back pressure. It's elimination can result in a fuel economy benefit of 2 percent. In addition, the SPI system results in reduced cold start enrichment requirements and less acceleration enrichment due to improved fuel atomization. These effects provide another 1 percent benefit, for a total of 3 percent. Many carburetted vehicles used pulse-air systems, so that their conversion to SPI did not include the benefit associated with air pump elimination, but did provide a modest back pressure decrease. For such vehicles, EEA has estimated a total benefit of 1.5 percent due to SPI largely from paired comparisons of 1984-1986 vehicles when conversion to SPI was the only change between otherwise identical vehicles in that time frame.

Multipoint fuel injection places the fuel injectors close to the intake valves of the engines, allowing very precise delivery of fuel to each cylinder. This results in further decreases to cold start enrichment and acceleration enrichment, and significantly improved control of fuel delivery during deceleration. These factors provide a 1.2 to 1.5 percent fuel economy gain, based on data provided by the manufacturers. However, MPI also allows the use of a tuned intake manifold optimized for airflow. Such a manifold can provide a significant benefit to maximum torque. Torque benefits are available even without a

tuned manifold since no intake air heating is required to vaporize fuel, and a colder denser air change increase the engine output. Regression analysis of 1988 engines showed the following benefits for MPI in specific output and specific torque relative to SPI, controlling for compression ratio:

	BHP/L	N-m/L
OHC	9.3%	2%
OHV	9.3%	3.4%

The OHC comparison is biased by the fact that more high performance engines (tuned for maximum BHP) utilize MPI rather than SPI. As a result, MPI shows a very significant rise in peak output of nearly 10 percent but only a 2 percent increase in torque. A more controlled comparison shows that MPI can provide a 3 percent increase in torque and a 6 percent increase in output. For a constant performance comparison, axle ratio must be reduced by 3 percent relative to an SPI engine of the same displacement.

Complete shutoff of fuel during deceleration is also possible with MPI. Some manufacturers believe that deceleration fuel shutoff causes unacceptable driveability, but it is used by others. Deceleration fuel shutoff can provide a one percent benefit in fuel economy. Accordingly, the total benefit of MPI over SPI is as follows:

Reduced cold-start and acceleration enrichment	1.20 to 1.50%
Decrease axle ratio by 2 to 3 percent	0.44 to 0.67%
Deceleration fuel shutoff	1.00 to 1.20%
Total	2.64 to 3.37%

EEA utilizes a 3 percent benefit estimate as an average. In 1986, when GM converted their 2.8L V-6 from a carburetted fuel system to a multipoint fuel injection system, they publicly claimed[5/] a benefit of 7 percent in fuel economy. This is in good agreement with the 3+3 percent (6%) estimated by EEA.

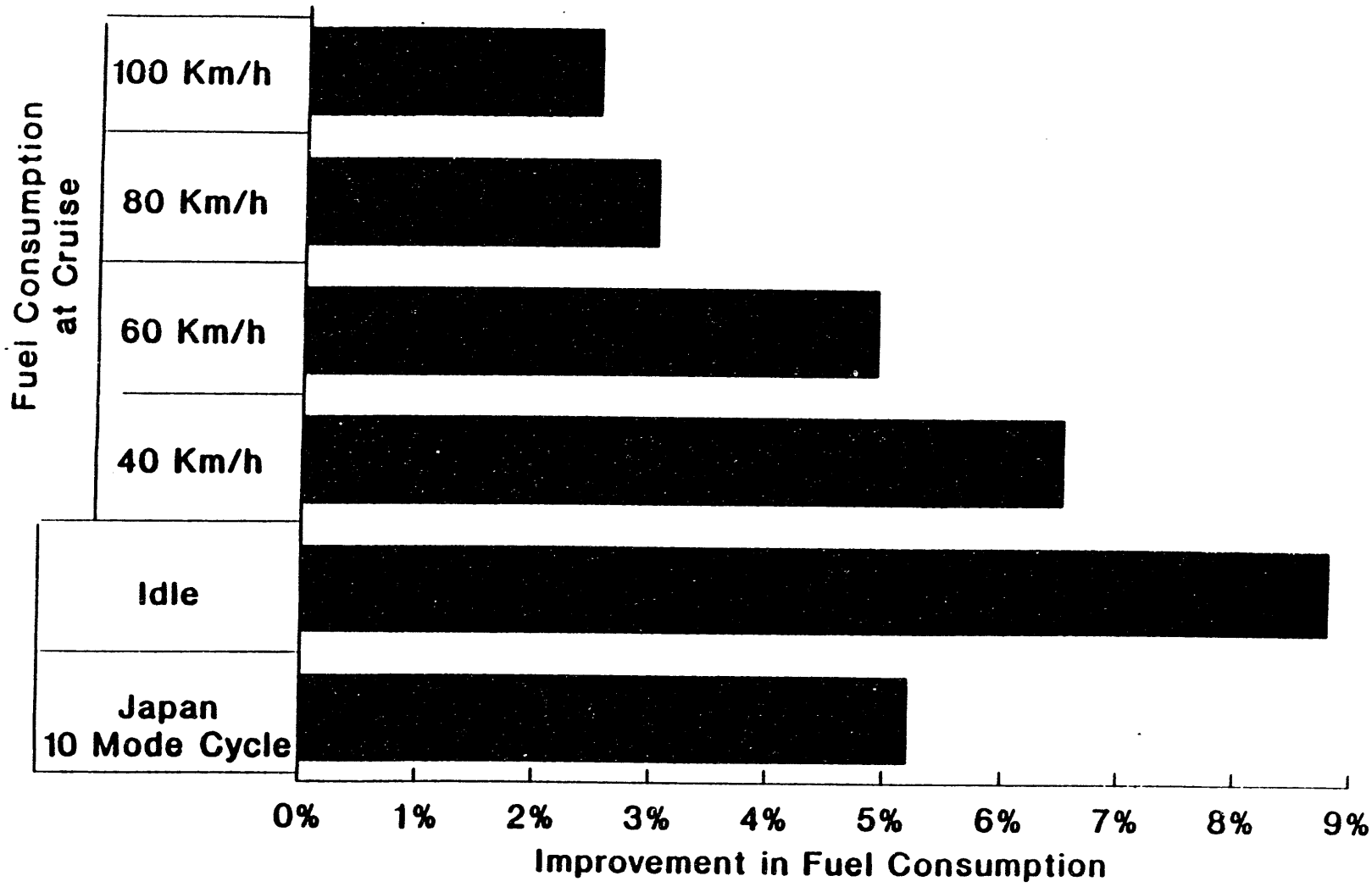
6.5 ENGINE FRICTION REDUCTION

Engine friction reduction is an ongoing effort and is made possible by evolutionary improvements to all parts in the engine that contribute to friction. At an engine speed of 3000 RPM, the major components accounting for total frictional losses are pistons/rings, valve train, crankshaft and oil pump, in that order. While the friction losses of most components increase non-linearly with engine RPM, valve train friction actually declines slightly in absolute terms and significantly as a percentage of total friction.

Because of its larger contribution to total friction at low speeds, valve train friction reduction provides large benefits on the test cycle where engine speeds are typically in the 1000-2000 RPM range. Roller cam followers provide very significant reduction in friction, and most domestic OHV engines have (by 1990) utilized this technology. Detailed analysis by DOT and manufacturer submissions to DOT show that the use of roller cam followers can provide a 1.5 to 3 percent improvement in fuel economy. This confirms an earlier (1982) analysis by Ford[6/], that showed a 2.9 percent fuel economy improvement due to roller cams at an engine speed of 1500 RPM. The use of roller cams in OHC engines is more recent, and has been adopted by Chrysler and Mitsubishi. Mitsubishi[7/] provided data on an OHC engine as shown in Figure 6-4, an it is claimed that the EPA test cycle fuel economy benefit is over 4 percent. Other manufacturers have suggested that the benefit is sensitive to the base (non-roller) design, and a median benefit estimate of 2 percent has been adopted by EEA.

Piston redesign and decreases in ring tension and ring width contribute to a reduction in friction. Ring tension reduction and redesign alone has contributed to a 1.5 percent increase in fuel economy in some engines already. Improved piston design and lighter weight pistons have contributed to an additional 0.5 percent. Typically, a 1988 4-cylinder engine has a friction mean effective pressure of 12 to 13 psi at 1500 RPM. Piston and ring redesign along with improvements such as:

Improvement in Fuel Consumption Due to Needle Bearing Roller Type Rocker Arm



SOURCE: Mitsubishi

FIGURE 6-4

- lightweight valves
- titanium valve springs
- composite lightweight connecting rod
- use of 2 rings instead of three
- half-speed oil pump
- low friction crankshaft seals

will all contribute to a 20 percent reduction in friction by 2001 (of course, individual engines may have larger or smaller reductions). A special low friction engine constructed by Ford[8/] recorded a 4.3 psi reduction in friction even without a 2-ring piston, with a claimed fuel economy benefit of 6.5%. EEA forecasts a total benefit of 4 percent through improved design and an additional 2 percent through the use of roller cam followers over the 1988-2001 period, consistent with Ford's estimate.

A separate issue centers around the reduction in number of cylinders. As engines of higher specific output and lower displacement are used, it would be reasonable to assume that a reduction in the number of cylinders is both feasible and likely. Consider a vehicle with an OHV 3.0L V-6 with an engine output of 135 BHP and 225 N-m of torque. This can be replaced by an OHC V-6 of 2.7L displacement providing 140 BHP and 220 N-m of torque, or by DOHC/4V engine of 2.4L displacement producing 149 BHP and 216 N-m of torque. The 2.4L engine can either be a V-6 or an I-4, and the I-4 would have lower friction. Based on friction data collected from different engines EEA estimated that the friction benefit could be 14 to 15 percent, to provide a 3 percent benefit in fuel economy.

Ford[9/] provided a detailed comparison of friction data for 2.3L engine in 4, 6 and 8-cylinder form. They also found that the larger bore of the 4-cylinder results in some thermal efficiency improvement. A similar comparison for a 4.5L V-6 vs. a 4.5L V-8 was provided and the data are shown in Table 6-2. The BSFC change for the smaller engine supports EEA's projections, but Ford

TABLE 6-2

EFFECT OF NUMBER OF CYLINDERS
ON FUEL ECONOMY

	4-cylinder	6-cylinder	8-cylinder
2.3 Liter			
Thermal Efficiency	0.366	0.363	0.358
Friction MEP (psi)	12.4	13.9	15.1
% Change in BSFC	Base	-3.2	-6.2
4.5 Liter			
Thermal Efficiency	--	0.366	0.366
Friction MEP (psi)	--	11.5	12.5
% Change in BSFC	--	Base	-1.6

Source: Ford Motor Co.

(See text about Ford's comments on idle and lug speed capability.)

claimed that the 4-cylinder would have higher idle and lug RPM levels than a V-6, negating this 3 percent benefit. (The same effect was claimed for the V-6 to V-8 comparison). EEA has examined available idle RPM data from 4 and 6 cylinder engines and found significantly smaller difference than claimed by Ford. In addition, we found that the 4-cylinder engine typically weighs 40-50 lbs. less than V-6 of equal displacement, and Ford had not considered this effect. Moreover, other automanufacturers do not subscribe to Ford's view. Toyota and Nissan engineers have commented that V-6's are less efficient in a comparison of 2L 4-cylinder and 6-cylinder engines. As a result, EEA has retained the 3 percent benefit estimate for reduction in number of cylinders. It is clear that 4-cylinder has inferior vibration characteristics relative to a V-6, and EEA recognizes that the fuel economy benefit does result in some reduction to consumer attributes. However, we note that other technologies for engine mounts may counteract this effect completely. The use of balance shafts on four cylinder engines will, however, negate the benefits of reduction in number of cylinders.

6.6 VARIABLE VALVE TIMING

Most spark ignition engines in cars used fixed valve timing and lift, i.e. the valve timing does not change with speed or load, and is generally set to a level that is a compromise between low seed torque and high RPM horsepower. It has been long recognized that closing the intake valve early at light loads would significantly reduce pumping loss, while variable valve timing could enhance both low speed torque and high speed horsepower with no necessity to compromise between the two.

While the maximum torque and horsepower potential from a given displacement engine are of interest, the principal benefit to fuel economy from variable valve timing is due to pumping loss reduction. At intermediate RPM, pumping loss is only 10 percent of indicated power a wide open throttle, but is 50 to 60 percent of indicated power at light load. In an analysis of the potential of early intake valve closing, Tuttle[10] found that there were also other benefits to thermal efficiency due to lower cylinder temperatures, as well as

increased turbulence in the combustion chamber. At light loads, a 10 percent benefit to bsfc was found (about 8 percent due to pumping loss reduction and 2 percent due to improved thermal efficiency). The lower temperatures also resulted in significant reduction in NO_x emissions.

In a review of work on variable valve timing, Gray[11] found that systems also offered improved and smoother running at low speeds, and that various devices that varied valve closing times, valve overlap and valve lift offered benefits in either power/torque or fuel consumption or both. Limitations on the extent of control and fuel economy improvement actually measured were the result of a lack of simple mechanism to continuously vary lift and timing.

Nissan was the first to introduce a variable valve timing system in the U.S. in the Nissan 300-Z equipped with a DOHC 3.0 Liter V-6. In this system, the inlet camshaft phase is changed by means hydraulic system. Published data[12] showed that at 2000 RPM, the variable valve timing system improved the torque by 8.5%, while still maintaining high maximum power and idle stability. (The torque benefit was 20 percent for the turbocharged V-6). This would suggest a 2 percent increase in fuel economy at constant performance, if axle ratio were reduced by 8.5 percent.

A more sophisticated valve control system has been available from Honda in its Japanese Civic. The system utilizes one cam-lobe to control one valve at low speed while disabling the second, and a separate lobe to control both intake valves at high speeds and loads. The Japanese Civic 1.6L engine employing the two position variable valve timing system in optimized for performance, and produce 160 HP, a 23 percent improvement over the standard Civic 1.6L. Torque is about 5 percent higher over the entire range of RPM. More recently Honda has introduced the VTEC 1.5L engine that is optimized for fuel economy.[13] Here torque is maximized, and the variable valve timing system provides approximately 15 percent better torque at 2000 RPM relative to the non-VTEC 4-valve engine, but has the same peak horsepower output of 92 HP. In fact the VTEC engine attains its peak output at 5500 RPM, while the non-VTEC engine attains it at 6000 RPM.

Prior to the introduction of the Honda Civic VTEC, a Ford review paper[14] suggested that an 80 percent reduction of pumping work was the maximum achievable and the theoretical fuel economy improvement was estimated at 6 percent. Reduced idle speeds and improved combustion could result is an additional 1 percent improvement. However, friction losses due to the valve control system were expected by Ford to make this benefit unattainable, so that only a 3 percent gain would be possible in real-life. The Ford analysis did not account for the increased low speed torque and potential engine downsizing capability.

The Honda VTEC Civic's fuel economy is 44 percent better than the DX model with an identical displacement engine. This very large gain in fuel economy is due not only to the VTEC engine but also due to a range of other technological improvements. The Civic VTEC vehicle is 125 lbs lighter than the Civic DX and features low rolling resistance tires and aerodynamic aids. The 49-state VTEC engine utilizes lean-burn as well as variable-valve timing, and the engine has low friction components. Finally, the gear ratios and axle ratio differ between the Civic VTEC and DX models.

A more comprehensive review of the VTEC will be undertaken to separate at the effects of all of the technologies. Currently, EEA has selected 6 percent benefit as the near figure for variable valve timing of which 3 percent is due to reduced part load pumping loss, and 3 percent due to an 8 percent reduction in engine displacement to maintain constant performance.

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7. IMPROVEMENTS TO AUTOMATIC TRANSMISSIONS

7.1 ENGINEERING DESCRIPTION

Improvements to current automatic transmissions can occur in the following areas:

- Increased penetration of torque converter lock-up.
- Reduction in flow losses in the torque converter.
- Increase in the ratio spread between top and first gear.
- Increase in the number of gear steps between the available limits.
- Electronic control of transmission shift points and torque converter lockup.

Current automatic transmissions use a hydraulic systems to transmit the engine power to the drivetrain. There is no direct mechanical linkage of the engine to the transmission; instead power is transferred by a torque converter. They flywheel, which is attached directly to the engine's crankshaft, also is bolted directly to a part of the torque converter termed the impeller. The impeller fan sets up a motion of the hydraulic fluid (transmission oil) and this in turn spins a centrifugal fan, which is not mechanically connected to the impeller.

During periods of acceleration, this hydraulic system allows the driven member (centrifugal fan) to turn more slowly than the driving member (impeller). This process is termed slip, but it also leads to torque multiplication. Although torque multiplication is useful during acceleration, the fuel economy of this system is degraded during cruise conditions when the torque converter begins to slip. This slippage causes a loss in fuel economy because, during constant speed conditions, it is more fuel efficient for both members to revolve at the same rate. In order to rectify this situation, automobile manufacturers have developed a system to mechanically link the driving members

during cruise periods. This system, termed a torque converter lockup, eliminates slippage and consequent fuel economy losses.

The fuel economy of manual and automatic transmissions can be improved by increasing the ratio spread between the lowest and highest gears. A larger ratio spread also needs to provide more intermediate gear steps to prevent excessive shift shock and poor driveability when gears are shifted. In addition, the lowered road load aerodynamic horsepower requirement from low aerodynamic drag designs also demand a larger ratio spread to provide better matching between load and engine operating point. At any operating condition, the vehicle demands a certain horsepower from the engine, and horsepower is the product of torque x engine speed. If fuel economy were the only concern, the optimum point to operate under any load condition is by maximizing torque and minimizing engine speed (RPM). This leads to reduced throttling loss and reduced friction loss. However, there must be sufficient reserve power at any operating point so that modest changes in road load horsepower do not require a downshift. In addition, operation at too low an RPM causes excessive driveline harshness and poor accelerator response. As a result, the choice of operating points is constrained. To maximize fuel economy and driveability, the drivetrain parameters of engine size, axle ratio, gear ratios and number of gears must be matched carefully. Table 7-1 shows the typical ratio spreads in U.S. domestic car transmissions used in 1988-1990. The Continuously Variable Transmission (CVT) can be visualized as the logical limit of increased number of gear steps, and it permits operation closer to the theoretical optimum.

Mercedes has offered 4-speed automatic transmissions since the early 1970's, but domestic manufacturers first introduced them in the early 1980's. As of 1988, 4-speed automatics are widely used in all domestic large and midsize cars but most domestic compacts and subcompacts use 3-speed automatics. Five speed manual transmission have completely replaced four-speed units, which are currently offered only in a special low price Escort. Torque converter lock-

TABLE 7-1

TYPICAL RATIO SPREADS

FOR TRANSMISSIONS IN 1988

	Automatic		Manual	
	3 speed	4 speed	4 speed	5 speed
Chrysler (FWD)	2.69	4.12	N/A	4.57
Ford (FWD)	2.84	4.01	4.12	4.80
Ford (RWD)	N/A	3.58	N/A	4.52
GM (FWD)	2.84	4.29	N/A	5.04
GM (RWD)	N/A	4.09	N/A	4.69

N/A - Transmission not used.

RWD - Rear wheel drive.

FWD - Front wheel drive.

up (TCLU) clutches are also widely used in most, but not all, transmissions. In fact, TCLU penetration declined slightly from the mid-1980's to 1988.

In the 1990's, further increases in ratio spreads and number of gears are likely. Mercedes-Benz and Nissan have recently introduced a 5-speed automatic transmission, while GM has introduced a 6-speed manual transmission. Product plans reveal that such transmissions are likely to be more widely adopted in the post-1995 timeframe. CVT's have been introduced in Europe and Japan, and in one car model in the U.S.

Electronic transmission control is also likely to become more widespread as a tool for optimizing the TCLU's lock-up speeds and the transmission's shift points. However, engineers believe that the current hydraulic system is well tailored to the FTP, so that electronic controls will be more effective in real-world conditions where non-FTP modes are encountered.

7.2 TORQUE CONVERTER LOCK-UP

Torque converter lockup clutches result in driveline vibrations being transmitted to the body. The locking-unlocking action can also be annoying because of the slight jerk to the vehicle. Thus, their use in small diesels or gasoline engines with fewer than 4-cylinders -- engines that have inherently high vibration levels -- are likely to cause more customer complaints than in a vehicle equipped with larger, smoother engines. In fact, in recent years TCLU's have been removed in some vehicles with 4-cylinder engines. However, reductions in 4-cylinder engine vibration levels and electronic control of lock-up can reverse this trend.

The fuel economy benefits of TCLU have been extensively studied by the automanufacturers in careful "back-to-back" tests with the TCLU engaged and disengaged on the same vehicle. Chrysler had provided data[1] on their first torque converter lock up clutch in 1978, where lock-up was applied in third gear only. Results showed a six percent improvement in the highway cycle and a two percent improvement on the city cycle for a net improvements of 3

percent. Ford introduced its automatic overdrive with lock-up in gears 3 and 4 in 1980. More recently, Ford's front-wheel drive four-speed transmission (called AXOD) has lock-up in gears 2, 3, and 4. The actual fuel economy benefit was found to depend on:

- The efficiency of the open converter
- The actual lockup speeds encountered in the city cycle

A review of the confidential submissions by the automanufacturers to DOT suggests that increased benefit of lock-up in gear 2 is partially offset by the increased open converter efficiency. The benefits may be slightly lower for four cylinder engines due to requirements for vibration and noise control. DOT has suggested a range of 3 to 5 percent benefit, and EEA's 3 percent estimate appears conservative in this light.

The design of the torque converter itself is being improved. Toyota[2] has introduced a new "Super Flow" converter in its Lexus LS400 vehicle. The new converter was computer designed to optimize impeller blade angle and blade shape to reduce loss of oil flow. In addition, the new manufacturing techniques were developed for the impeller to increase rigidity. As a result, Toyota claims the converter efficiency is the world's best, and is 3 to 5 percent higher than other torque converters. Such an improvement is expected to provide a 0.5 percent benefit in composite fuel economy.

7.3 FOUR/FIVE SPEED AUTOMATIC TRANSMISSION

The effects of increased number of gears in a transmission is dependent on several variables that define the transmission. The increased number of gears can be utilized to provide a wider ratio spread between first and top gears, or else to increase the number of steps with a constant ratio spread for improved driveability and reduced shift shock. In addition, the wider ratio spread can be utilized to provide higher performance in the first few gears while keeping the ratio of engine speed to car speed in top gear constant, or else to keep performance in the first few gears constant and reduce engine speed in top gear. Since the manufacturer is able to select among these

tradeoffs, different manufacturers have chosen different strategies in selecting gear ratios.

An overdrive transmission (manual or automatic) needs careful matching to engine characteristics and axle ratio to provide optimum fuel economy gains. In general, the use of overdrive results in lower engine speeds on the highway which, in turn, decreases noise and vibration levels. However, performance in overdrive also suffers and downshifts are required to negotiate gradients or provide highway passing performance. In city driving, overdrive is of little value, since vehicle speeds are never high enough to spend any substantial portion of urban mileage in overdrive.

In keeping with the constant performance criterion, EEA has examined fuel economy differences between 3 and 4 speed automatic transmissions where the performance in the first three gears is nearly identical. In examining the available 3-speed and 4-speed transmissions for domestic automobiles, we have found that the first three gear ratios are nearly identical between the two transmission types, while the 4th gear is usually an overdrive with a ratio of 0.66 to 0.75.

Among the earliest studies on the effects of number of gears and ratio spread was a theoretical study by Chana, Fedewa and Mahoney[3] from GM. In this study, engine size and axle ratios were optimized for maximum fuel economy, as was the shift pattern. In real life, these choices are not unconstrained, and other parameters related to vehicle driveability and comfort limit the number of shifts during normal driving. Hence, the study can be considered as an upper bound to the benefits obtained. The study compared a 3-speed automatic with 2.84 ratio spread to a 4-speed automatic with 4.22 spread. These values are very similar to the actual values in transmissions available today. The 4-speed unit was found to provide 14.3% benefit in composite fuel economy over the 3-speed unit when evaluated at constant performance as defined by the 0-60 mph acceleration time. In practice such values have not been attained.

Since both 4-speed and 3-speed automatic transmissions are already sold widely in the U.S., a comparison of vehicles featuring these transmissions is possible. Unfortunately, both transmissions are rarely available in the same carline/engine combination. A "matched pair" is required so that vehicle differences and performance differences are factored out of the comparison.

Only GM and Toyota have offered both transmissions with the same carline/ engine in the 1986-1989 period. The GM transmissions have nearly identical ratios for the first three gears, but the 4-speed features on overdrive gear with 0.70 ratio. In the Toyota, the 4-speed transmissions first gear has a 2.45 ratio versus 2.91 for the 3-speed transmissions. The shift schedule is an uncontrolled variable in these comparisons. In addition, the axle ratios also differ slightly. In all cases, the "constant performance" criterion is only approximately valid. In addition, measurement variability can cause errors of ±2% of the actual (true) value. As can be seen from Table 7-2 the available comparisons show a range of 3 to 7.8 percent benefit for the 4-speed over the 3-speed. Conversations with transmission engineers suggest that 4.5 percent is an acceptable median value for a constant performance comparison. A more recent EPA "matched pair" comparison[4] has come to a similar conclusion.

Five speed automatic transmissions have only recently been commercialized in Japan and Europe. Nissan has provided a comprehensive analysis of the effect of numbers of gears and choice of first gear and top gear ratios on fuel economy.[5] They found declining benefits with increasing number of gears, with little or no benefit above six gears. With a first gear ratio of 3.0 (similar to that of current automatics) they found no benefits in fuel economy in using overdrive ratios lower than about 0.7. However, increasing the first gear ratio to about 4 provided better standing start performance. This production Nissan 5-speed transmission uses a 3.85 first gear ratio and a 0.69 overdrive ratio for a 5.56 ratio spread. At constant performance, Nissan showed fuel economy gains in the 3 percent range. Mercedes, the only other manufacturer to have introduced a 5-speed automatic, confirmed that the fuel economy benefit over a 4-speed automatic was in the 2 to 3 percent range.

TABLE 7-2

MATCHED PAIR COMPARISONS OF FUEL ECONOMY WITH THREE- AND FOUR-SPEED AUTOMATIC TRANSMISSIONS

Model	Engine CID	Test Weight (lb)	3-Speed Auto		4-Speed Auto		% F/E Increase
			Axle	F/E	Axle	F/E	
Chevy Celebrity	173 V-6 (2-bbl)	3250	2.84	25.5	3.06	26.5	3.9
Olds Cutlass	173 V-6 (FI)	3250	2.84	24.2	3.06	26.1	7.9
Chevy Caprice	262 V-6 (FI)	4000	2.56	21.7	2.56	22.7	4.6
Chevy Caprice	262 V-6 (FI)	3875	2.56	23.2	2.56	23.9	3.0
Toyota Corolla	97 I-4 (FI)	2750	3.33	33.1	2.82	34.9	5.4

Ford also submitted data on their planned 5-speed automatic transmission. Although the specific gear ratios were not provided, Ford provided simulated data on the 4-speed and 5-speed transmissions. They found the benefits to be closely related to the absolute performance level at which the comparison was made. As shown in Figure 7-1, Ford estimated that the 5-speed automatic would provide a 2.5 percent at current performance levels, but could have much smaller benefits at other levels. It is possible that the ratio spreads between the two transmissions did not differ much in this comparison.

EEA has selected 2.5 percent fuel economy benefit as a representative figure for the fuel economy benefit of a 5-speed automatic over a 4-speed automatic.

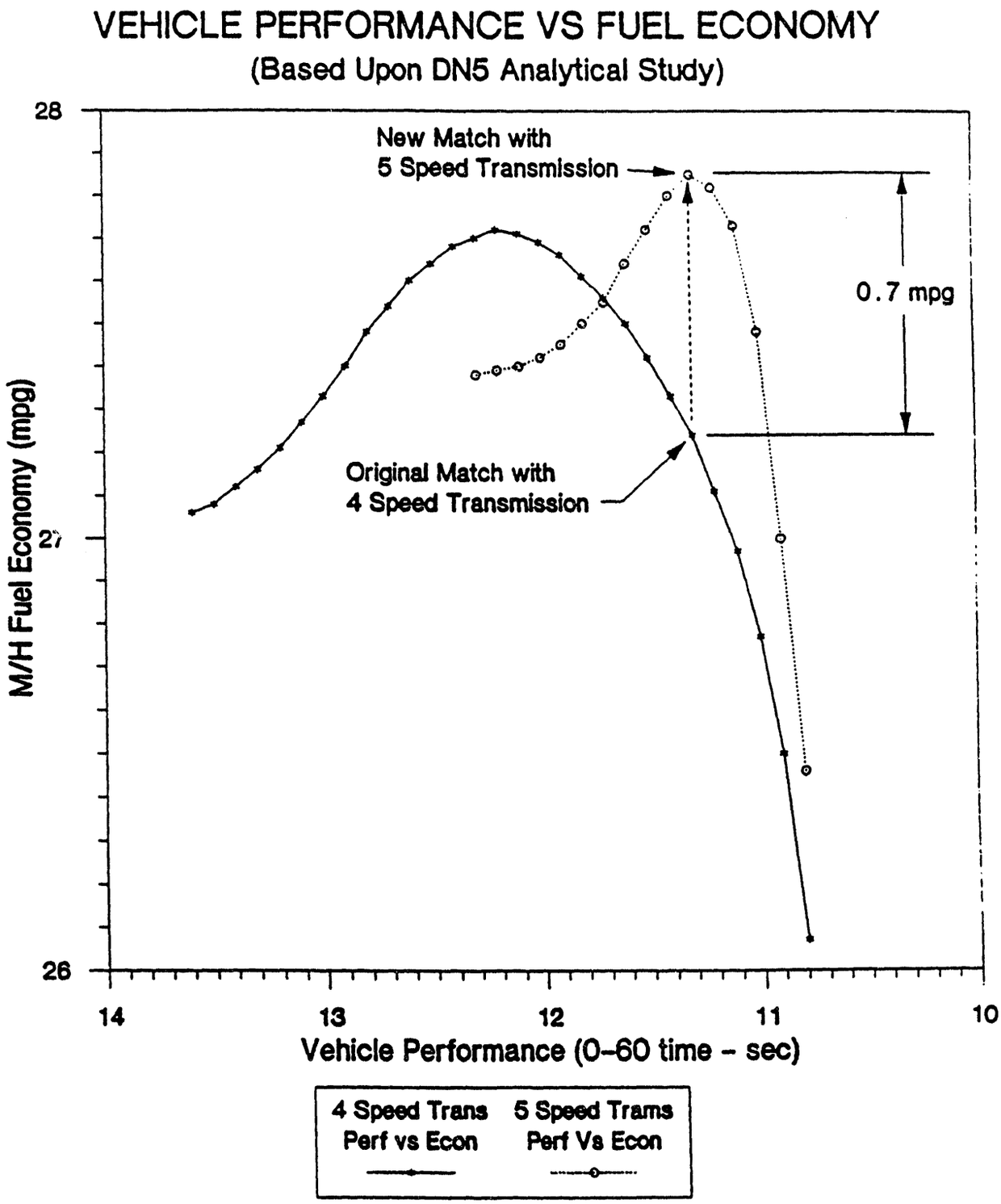
7.4 ELECTRONIC TRANSMISSION CONTROL

Electronic Transmission Control (ETC) systems can replace the hydraulic controls used in most transmissions. The electronic system can be used to control shift schedules and torque converter lock-up such systems were first introduced in Toyota's A43DE transmission in 1982. As of 1988, the domestic manufacturers did not have electronically controlled transmissions although several have been introduced in 1989 and 1990.

The benefit of the ETC system lies in the potential to maximize fuel economy by tailoring shifts and lock-up to the driving schedule. In the analysis of Toyota's 4-speed transmission in 1982[6], the benefits of the electronic transmission control in "normal" setting offered a 3.1 percent in fuel economy or the Japan 10-mode city cycle. Benefits on highway driving schedules are much smaller, simply because there are fewer gearshifts. Toyota also found that in an "economy" setting, the benefit increased to 6.2%. DOT has published estimates of 3 to 5 percent benefit in fuel economy for the ETC system.

Domestic automanufacturers, however, claim that these benefits are unrepresentative since most modern non-electronic transmissions have been optimized for the FTP test cycle, and the available benefits of ETC are much smaller. Although several electronically controlled transmissions are already

FIGURE 7-1



November 22, 1989
Powertrain Systems Analysis Department

available, "paired sample" comparisons are not possible as no example of the same car/engine combination is available with non-electronic and electronic transmissions. However, studies across different models of similar weight and performance do not show any significant advantages for the electronic transmission. In the absence of carefully controlled test data, we have accepted the manufacturer's claim that the benefit is only 0.5 percent. However, it appears there is potential for greater improvement with some loss of smoothness or "feel".

7.5 CONTINUOUSLY VARIABLE TRANSMISSIONS

Current transmissions feature a discrete number of gear ratios (usually 3 to 5) that determine the ratio of engine to vehicle speed. This results in some loss of flexibility in matching the engine speed/load condition to vehicle requirements. A continuously variable transmission (CVT) offers a infinite choice of ratios between fixed limits, allowing optimization of engine operating conditions to maximize fuel economy.

Currently, Subaru is the only manufacturer offering a CVT in a small car. Although there are several designs being tested, the CVT that is in production features two conical pulleys driven by metal belts. The position of the belts on the conical pulleys determine the gear ratio between input and output shafts. Under steady state conditions, the metal belt system can be less efficient than a conventional system, but the fuel used over a complete driving cycle is decreased because of the optimized speed/load conditions for the engine.

Current CVT's are designed as replacements for conventional automatic transmissions and are generally not more efficient than a wide ratio 5-speed manual transmission or an advanced overdrive five speed automatic transmission. The CVT is expected to find application only in small cars because: 1) CVT's are inherently torque limited due to the metal belt design and are, thus, not compatible with engines over 2 liters (120 CID) in displacement; and 2) CVT's are attractive for small front-wheel drive cars because they are

easier to "package" than a four-speed or five-speed automatic transmission. The performance, cost and fuel economy gains are discussed below.

Several major suppliers are experimenting with CVT's, and Ford and GM are known to be testing the CVT for possible introduction in the mid-1990's in the subcompact and minicompact class of cars. Ford offers a CVT in its European Fiesta as of 1990.

Performance of the CVT should be equal to or somewhat better than conventional automatic transmissions. However, a CVT can produce unexpected changes in engine speed -- i.e., engine speed dropping while the vehicle speed is increasing -- which may deter consumer acceptance. Developments in the metal belt system coupled with weight reduction of future cars are expected to enhance the availability of the CVT for use in the compact size classes of cars in the 2000 time frame.

In the early 1980's, CVT's were expected to provide substantial fuel economy benefits over 3 speed automatic transmissions. Researchers from Ford[7] showed that an Escort with a CVT of 82 percent efficiency would have a fuel economy 14 percent higher than the fuel economy with a 3-speed automatic; at a CVT efficiency of 91 percent, the fuel economy benefit was computed to be 27 percent. (91 percent was considered as an upper bound of potential efficiency). Similarly, Gates Corporation[8] installed a CVT in a Plymouth Horizon and found a fuel economy improvement of 15.5 percent over a conventional 3-speed automatic with lock-up at almost identical performance levels. However, design compromises for driveability, as well as improvements to the base three speed automatic since the time these papers were published (1982) has resulted in lowered expectations of benefits. The current consensus among automanufacturers is that the CVT will be 8 to 10% more efficient than current 3-speed automatics with lock-up, and EEA has utilized 8.5 percent as a conservative figure. This figure is consistent with the measured results from the Subaru Justy CVT sold in the U.S. Note that the 8.5 percent figures includes the benefits of electronics control which is required to maximize CVT benefits.

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8. DIESEL ENGINES AND TWO-STROKE ENGINES

8.1 DIESEL ENGINES

The diesel engine uses a fundamentally different combustion process than the spark-ignition (gasoline) engine. In the diesel, intake air is heated by compression to a temperature sufficient to ignite the fuel. Diesel fuel is then injected as a spray at very high pressure, with combustion taking place at the air-fuel interface of the spray droplets. (In spark-ignition engines, air and vaporized fuel are pre-mixed, and the homogenous mixture is ignited by a spark).

The diesel inherently is more efficient than spark-ignition engines as a power plant for motor vehicles. First, the diesel has a greater thermodynamic efficiency because it operates at much higher compression ratios than a gasoline engine (22:1 versus 8:1). Second, current diesels are unthrottled and achieve part-load operation by reducing the rate of fuel injection, therefore leaning the air-fuel ratio. In contrast, gasoline engines throttle the intake during part-load operation, incurring pumping losses associated with airflow pass the throttle plate, and maintain approximately constant air-fuel ratios across the operating range. Diesels therefore, offer particularly efficient operation during idle and low-load conditions, which are very common in urban driving patterns.

Since the diesel combustion process is controlled by the rate of fueling, performance of the injection system is critical. All of the current passenger car diesels feature a pre-chamber design in which the air and fuel spray are partially mixed and ignited before combustion spreads to the main chamber. This design limits the rapid pressure rise which occurs in a direct-injection diesel (found in medium and heavy-duty trucks), with attendant reductions in noise, vibration, and NO_x emissions. The prechamber design also makes the combustion process less sensitive to the performance of the fuel injection

system and allows the use of a less expensive rotary injection pump. However, the lower rate of pressure rise and the additional heat transfer of the prechamber design results in lower specific fuel economy than in the direct injection diesel.

Diesel engine performance traditionally has been a deterrent to its widespread acceptance. The principal disadvantages of the diesel compared to gasoline engines are:

- Poor acceleration
- Increased noise and vibration
- Cold start performance
- Exhaust smoke and odor

Performance advantages for the diesel include reduced maintenance and better throttle response which eliminates stumbling and hesitation in any weather.

Acceleration performance has ben poor because diesels have significantly lower peak power output than gasoline engines of equal size (displacement), due to the higher internal friction of the diesel engine as well as limitations on the diesel combustion process. In particular, smoke production increases at high fueling rates due to incomplete combustion of the injected fuel droplets. The engine design must therefore limit peak power to control smoke to acceptable levels. A diesel engine is also heavier than an equivalent gasoline engine to withstand the higher stresses of the increased compression ratio, with a resulting adverse impact on power/weight ratios. Diesel performance can be increased by using a larger engine or by turbocharging, although with price and fuel economy penalties. During times of high fuel prices, however, consumers have been willing to accept reductions in traditional performance in return for increased fuel economy.

Although diesels have increased noise and vibration levels, insulation and rubber engine mounts have successfully minimized these problems in current cars so that the average driver cannot differentiate between gasoline and

diesel engines. Slow cold start and warm-up performance of diesels have been improved through the use of EGR. GM already has developed a "fast-start" glow plug system that allows the diesel to start in 60 seconds in 0 degree weather. Exhaust smoke and odor are problems that are less readily solved, but it appears that particulate traps (addressed elsewhere in this section) will provide control of both.

Although diesels traditionally are thought to be 25 percent more efficient than gasoline engines, comparisons from currently available models show that the fuel economy gain can range from 15 to 55 percent, depending on the type of comparison being made.[1] (Equal engine size, equal performance, or model to model comparisons produce very different results.) One problem with comparing diesel to gasoline fuel economy is that diesel and gasoline versions of the same car rarely exhibit similar performance characteristics, while comparisons between different models can reflect manufacturer and drivetrain differences. The limited number of diesel models available also make accurate comparisons difficult. In fact, in 1987 only four diesel car models were available and all of these models were phased out by 1989.

Comparison of actual data on all four cars from model year 1987 with their gasoline counterparts is provided in Table 8-1. The Ford Escort comparison is the only one for a naturally aspirated diesel, but the performance levels of the gasoline and diesel cars are very different, as is obvious from the comparison of horsepower and torque. In all of the cases considered, the diesel vehicle is heavier by 125 lb than its gasoline counterpart. The comparisons of the two Mercedes and one Peugeot are closely representative of a constant performance situation. This indicates that at constant performance a turbocharged diesel can provide 20 to 36 percent better fuel economy than an equivalent technology gasoline counterpart. Diesel experts have concluded that 30 percent benefit for a turbocharged diesel is the correct figure for engine of similar design quality.

In addition, diesels have much lower fuel economy shortfall (difference between real-world and EPA fuel economy), than gasoline engines. This

TABLE 8-1

COMPARISON OF DIESEL/GAS FUEL ECONOMY - 1987 CARS

	Ford Escort		Mercedes 190 2.3/2.5D		Mercedes 260E/300D		Peugeot 505	
	Gas	Diesel	Gas	Diesel	Gas	Diesel	Gas	Diesel
Type	OHC	OHC	OHC	OHC/Turbo	OHC	OHC/Turbo	OHC	OHC/Turbo
Displacement	113	122	140	152	158	183	120	152
Horsepower	84	58	130	123	158	143	97	95
Torque (ft-lb)	105	84	146	162	162	195	116	133
Test Weight	2625	2875	3250	3375	3625	3750	3375	3500
Dyno HP	7.5	6.8	8.2	8.2	7.5	7.5	10.3	10.3
Transmission	M5	M5	A4	A4	A4	A4	L4	L4
Axle Ratio	3.52	3.52	3.27	2.65	3.27	2.65	4.11	3.89
City F/E	31.4	40.7	23.0	31.5	21.6	28.7	22.3	27.2
Highway F/E	47.2	57.3	30.7	41.5	29.9	37.9	30.5	35.9
Composite F/E	37.0	46.8	25.9	35.3	24.7	31.8	25.4	30.5
Diesel Benefit (%)	--	26.5	--	36.3	--	28.7	--	20.1

difference in shortfall ranges from 6 percent (for low fuel economy cars) to 25 percent for high fuel economy cars. Diesels especially show fuel economy advantages in city traffic, as they use very little fuel during idle, and in comparison to gasoline engines, also use much less fuel during the cold start and warm-up phase. In real world economy, therefore, the turbocharged diesel can provide up to 50 percent improvement over gasoline engines in an "average-to-average" comparison.

As explained previously, all of today's passenger car and light truck diesels are of the prechamber type. Conversion to direction injection results in an additional 15 percent fuel economy benefit over an equal displacement pre-chamber design. This large benefit has resulted in considerable interest in applying direct-injection to cars and light trucks, and there are several models currently undergoing development. Much of the work is being performed in Europe by AVL, BMW, VW and MAN.[2/3]

The direct injection diesel has suffered from the problems of increased noise and vibration as well as higher particulate emissions. The key to control of these problems lies in the fuel injection system. The use of electronic control and more advanced injection pumps has resulted in improved potential for the direct injection diesel. The status of current research shows that direct injection diesels are very close to meeting all applicable U.S. emission standards, while noise and vibration levels are competitive with current prechamber engines.

It appears that direct injection diesels could be introduced in the early 1990's by several foreign manufacturers for the U.S. market of these is a demand for such vehicles.

8.2 TWO-STROKE ENGINES

The two-stroke engine has recently made a reappearance, largely due to the success of an Australian firm, Orbital Engine Company. Historically, two-stroke engines had high specific output, low weight and were simple in design,

but had poor thermodynamic efficiency and very high emission levels. Orbital claims to have solved the problems by using a direct injection, stratified charge combustion system to reduce emissions and raise fuel efficiency.

According to information publicly available from Orbital,[4] a 1.2L engine has been developed fully to meet even the stringent 1994 U.S. emission standards of 0.25 HC/3.4 CO/0.41 NO_x g/mile. The Orbital engine has an output of 90 BHP and a torque of 130 N-m, roughly comparable to a 1.6L 2-valve OHC engine. Orbital claims that its principal advantages in fuel efficiency lies in decreased pumping losses and reduced mechanical friction. The thermodynamic advantages of direct-injection stratified charge engine arises from the lean burn concept used, but this is partially offset by the reduced effective compression ratio of the engine (~8).

In comparisons with the 1.6L 2-valve OHC engine, Orbital has claimed a bsfc advantage of 12 percent. In addition, the engine has an weight advantage of 120 lb and is reportedly smoother than the 4-cylinder 4-stroke engine. The size of the engine is also significantly smaller, and Orbital has claimed potential aerodynamic advantages of the engine. Even if this is discounted, the Orbital engine appears capable of providing a 16 to 17 percent total fuel economy advantage in a 2500 lb. inertia weight subcompact. The engine may be cost competitive with OHC 2- valve 4-stroke engines, although there is an initial tooling cost associated with conversion that may be significant. The Orbital claims have been apparently verified by automanufacturers, but they have issued no independent confirmation of these claims.

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9. POWER BOOSTING

9.1 TURBOCHARGING

9.1.1 Engineering Description

Internal combustion engines, both gasoline and diesel, reject 25 to 50 percent of the fuel energy into the exhaust. A turbocharger recovers some of this wasted energy, thereby increasing the power rating of the engine. The turbocharger consists of a turbine placed in the exhaust path which drives a compressor in the intake manifold, compressing incoming air to the engine. The higher pressure of the intake manifold results in more air being forced into the engine, thus generating more power.

The turbocharger can be used to improve performance or fuel economy. Its use as a performance device is obvious. As a fuel economy device, the turbocharger allows the use of a smaller, lighter engine without a performance sacrifice. Smaller engines with turbochargers have lower fuel consumption during idle and cruise conditions that larger, naturally aspirated engines of equal power. Depending on the choice of engine and turbocharger, performance can be traded off against fuel economy.

9.1.2 Application

Turbochargers function more effectively with diesel engines than with gasoline engines for two reasons. First, since the turbocharger compresses intake air, its effects on combustion are similar to that of an engine operating at increased compression ratio. Gasoline engines are compression limited by "knock" and the pressure boost delivered by the turbocharger must be carefully controlled to a low value (5-7 psi) to prevent knock. No such limitation exists for diesel engines, and turbocharger boost is only a function of engine material limitations. Second, gasoline engines throttle the intake air at part load conditions, whereas diesel engines reduce only the fuel delivered. Intake air throttling renders a turbocharger ineffectual and hence, the

turbocharger is utilized only under relatively infrequent wide-open throttle conditions in gasoline engines.

There are a number of problems associated with turbochargers, some of which are a result of natural laws governing the performance of turbines. For example, the complex interrelationship between boost pressure, airflow and turbocharger speed (RPM), results in a turbocharger providing little or not boost at low engine speeds and a very rapid rise in boost at high engine speeds. The conflict between boost and engine speed requires careful matching between turbocharger size and engine RPM to maximize mpg and performance benefits. The turbocharger's performance, cost and fuel economy gains are sensitive to the conflict between boost and engine speed design tradeoffs. The tradeoffs are discussed below, and the performance and fuel economy issues are highlighted.

As manufactures phase out the large V-8 engines, they have begun offering turbocharged gasoline engines to satisfy customers requiring performance. Both GM and Ford have offered turbocharged engines for over 10 years, and a number of European importers (Audi, Saab, Porsche) have offered them in expensive high performance cars. Turbocharged diesel engines are offered by Mercedes, Peugeot and Toyota. Total market penetration of turbocharged engines has been very small (2 percent in 1988). The reasons for the turbocharger's limited penetration are considered below.

9.1.3 Performance and Fuel Economy

The acceleration characteristics and fuel economy gains are dependent on how the turbocharger is "matched" to the engine. If the turbocharger is sized to provide boost at moderate engine speed (2000 to 3000 RPM) but sacrifice some maximum power at higher engine speeds, the engine will provide good performance in the 40 to 70 mph range. At the very low RPM range (for example, a hard acceleration from a stop sign), the engine behaves like a normally aspirated engine of identical size. After the vehicle exceeds 25 to 30 mph, it behaves like a larger normally aspirated engine. The EPA fuel economy gain

is approximately 5 percent over the larger normally aspirated engine of the same power. Mid-range boost offers the best compromise between fuel economy and performance. However, the turbocharger in combination with 4-valve engines exacerbates the low RPM torque problem. As a result, EEA does not believe that the turbocharger/4-valve engine combination will be used for fuel economy.

If all the boost is concentrated on the high end of the engine RPM range to optimize for maximum power, there is no gain in either performance or EPA economy during normal driving in comparison to a naturally aspirated engine of equal displacement. All the performance improvement is available only for high RPM gear shifting, and the turbocharger appeals to a performance oriented group of buyers. For example, the behavior of the now discontinued Mustang Turbo at low to moderate engine speeds resembles that of the naturally aspirated engine from which it was derived. Although fuel economy comparison with a V-8 shows a 10 percent gain, there are considerable differences in low speed acceleration between the two. It is clear that for gasoline engines the characteristics of the turbocharger appeal only to those buyers interested in maintaining high performance. For such customers, the turbocharger provides a 10 percent fuel economy benefit over a V-8, albeit at the expense of poor performance over a significant portion of the engine's speed range. Some 4-valve engine, such as the Toyota Celica 4WD engine, feature turbocharging to provide very high peak power.

Diesel turbocharging results in a price impact very similar to that for gasoline engines for modest maximum boost pressures (10-12 psi). At a higher boost pressure, piston cooling requirements and strengthening of internal engine parts as well as cooling system improvements may raise the price significantly. High boost pressures allow diesels to be competitive in acceleration performance with gasoline engines and the price is illustrative of the cost/performance tradeoff that customers will face in the future. For example, Peugeot has chosen the modest boost path, while BMW has chosen to use high boost to maximize performance. On average, EEA estimates that a turbocharger will provide a 10 percent benefit in fuel economy for diesels.

9.1.4 Environmental Constraints

The effect of turbocharging on emissions is dependent on the application. For gasoline engines, turbocharging can increase emissions for two reasons. First, the thermal mass of the turbine wheel in the exhaust delays catalyst warm-up, increasing HC and CO emissions. Second, if a smaller, more highly loaded engine is used (i.e., the turbocharger is used as a fuel economy device), NO_x emissions will increase. If the engine is not more highly loaded (i.e., the turbocharger is used to provide extra performance only), the turbocharger does not affect emissions on the EPA test cycle as there are no "wide open" throttle driving regimes during the test.

For diesel engines, the use of the turbocharger as a combination fuel economy/performance device typically results in decreased HC and particulate emissions due to the extra air available for combustion. NO_x emissions may increase, but only by a small percentage. Thus, in general, the use of turbochargers on diesels result in more favorable emission characteristics.

9.2 OTHER SUPERCHARGING TECHNOLOGIES

Although the turbocharger is the most widely used form of supercharger, several other supercharging technologies are being researched. The most important technologies are:

- Comprex
- Roots blowers
- Positive displacement pumps

These technologies are being investigated to eliminate the turbocharger's problems of poor low end torque and difficulty of matching with piston engine requirements.

9.2.1 Comprex

Comprex superchargers have been investigated for decades in Europe, principally by Brown-Boveri and MAN. They utilize the pressure pulsations in the

exhaust manifold to compress intake air in a rotating device that actually places the intake and exhaust gases in contact with each other. This also results in some mixing of exhaust gases with the intake air. Although the Comprex has worked in diesel engine applications, it has been difficult to control and has proven expensive. EEA is of the opinion that it is likely to be available in the post-1995 time frame, in some diesel models from Europe.

9.2.2 Roots Blowers

Roots blowers have been in use in aircraft engines since World War II and in limited production automobiles (such as Bentley and Mercedes) in the early 1930's. There has been renewed interest in this device recently, and Ford has introduced this technology into the market in 1990. The Roots blower is similar to a gear pump in operation, and consists of two lobe rotors geared together and enclosed in a housing. The rotors are connected to the engine crankshaft via a toothed belt and their rotation provides compression of intake air. Roots blowers are considerably bulkier than turbochargers and require precision castings and pressure seals for proper operation. However, they provide constant boost over much of the engine operating range, except at very low speeds where air leakage past the rotors results in very low boost.

9.2.3 Positive Displacement Pumps

Positive displacement pumps are similar to air pumps used in current vehicles for emission control. Supplier companies have been developing these pumps (vanetype) for use on superchargers. As with Roots blowers, they are bulky and need to be driven off the crankshaft. They are cheaper to produce than Roots blowers and produce somewhat higher low-speed torque. However, their durability characteristics are inferior to Roots blowers.

9.2.4 Application

Competition between Roots blowers and vane pumps for the gasoline supercharger market is likely. Since their size increases linearly with engine size, they become much too bulky for use with large engines. In addition, since they are driven off the crankshaft, the drive system becomes too complex to transmit

the high power required. For these reasons, EEA believes that superchargers (either Roots or vane-type pumps) may be used in small and compact cars as well as small LDT's. In both categories the application of superchargers can be combined with engine downsizing/axle ratio reduction to provide increases in fuel economy. Ford is using superchargers with a large V-6 (3.8L) engine, and the results have been mixed.

Unlike turbochargers, these supercharging technologies are more compatible with gasoline engines since diesels have much higher airflow at the same power, requiring greater power input to the supercharger. EEA estimates that superchargers can provide a 5 percent gain in fuel economy for gasoline engines for constant performance comparisons. However, superchargers may be offered as an option to increase performance, and reduce this benefit. Consumer prices for the supercharger are $250 to $300 depending on application. The Roots blower is likely to be more expensive but offers greater durability and quieter operation. The cost and complexity of supercharging will result in these technologies being used as a limited high performance option, rather than as a fuel economy device.

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ANALYSIS OF THE FUEL ECONOMY BOUNDARY FOR 2010 AND COMPARISON TO PROTOTYPES

DRAFT FINAL REPORT

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TABLE OF CONTENTS

	Page
1. INTRODUCTION	1-1
2. REVISED FORECAST OF FUEL ECONOMY FOR 1995/2001	2-1
2.1 Methodology	2-1
2.2 Technology Update	2-2
2.3 Revised Forecasts for 2001	2-7
2.4 Results	2-12
3. CALCULATION PROCEDURE REVISIONS FOR FUEL ECONOMY ESTIMATION	3-1
3.1 Overview	3-1
3.2 Engineering Model	3-2
4. ADVANCED TECHNOLOGIES TO IMPROVE FUEL ECONOMY IN THE POST-2000 TIME FRAME	4-1
4.1 Overview	4-1
4.2 Weight Reduction	4-2
4.3 Aerodynamic Drag	4-10
4.4 Driveline and Tire Losses	4-11
4.5 Conventional Engine Technology	4-12
4.6 Alternative Engines	4-18
4.7 Energy Storage/Idle Shutoff	4-26
5. FORECAST OF FUEL ECONOMY FOR 2010 AND COMPARISONS TO ADVANCED PROTOTYPES	5-1
5.1 Analysis Overview	5-1
5.2 Risk-Based Levels of Fuel Economy for 2010	5-2
5.3 Comparison of Forecasts to Prototype Fuel Economy	5-15

LIST OF TABLES

		Page
Table 2-1	Technology Definitions	2-3
Table 2-2	Technological Benefit Estimates Utilized	2-8
Table 2-3	Revised Projection - U.S. Domestic Manufacturers 1995 Product Plan Case	2-13
Table 2-4	Revised Projection - Potential U.S. Fuel Economy in 2001 Under Alternative Scenarios	2-15
Table 3-1	Technology/Energy Use Relationship	3-11
Table 3-2	Fuel Economy Cycle Characteristics	3-13
Table 3-3	Estimated Fuel Consumption Sensitivity Coefficients	3-17
Table 4-1	Material Use in Domestic Cars	4-3
Table 4-2	Packaging Efficiency of 1989 Cars	4-7
Table 4-3	Summary of Engine Improvements	4-19
Table 4-4	Comparison of Diesel/Gas Fuel Economy - 1987 Cars	4-23
Table 5-1	Characteristics of Baseline Cars Used for 2010 Forecast	5-5
Table 5-2	2010 Assumptions on Technologies at Different Risk Levels	5-8
Table 5-3	Fleet Fuel Economy in 2010 at Different Risk Levels	5-14
Table 5-4	Characteristics of High Fuel Economy - Prototypes	5-17

LIST OF FIGURES

		Page
Figure 3-1	Vehicle Resistance in Coastdown Test	3-4
Figure 3-2	Engine Speed - Proportion of Engine Friction Due to Valve Train	3-7
Figure 3-3	Improvement in Fuel Consumption Due to Needle Bearing Roller Type Rocker Arm	3-8
Figure 4-1	Material Mix for Various Vehicle Projections	4-9
Figure 4-2	Effects of High Compression Ratio	4-13
Figure 4-3	Reduction in Friction Mean Effective Pressure	4-16
Figure 4-4	Influence of Reduced Friction on Fuel Consumption as a Function of Engine Load	4-25
Figure 5-1	Typical Market Penetration Profile of New Technology . . .	5-10

1. INTRODUCTION

Concerns about the security of petroleum supply to the U.S. and about global warming due to greenhouse gas emissions of carbon dioxide have led the U.S. Department of Energy (DOE) to evaluate the potential to improve fuel economy of automobiles. The DOE is also required by legislation to comment on all rulemaking on Corporate Average Fuel Economy. As a result, the DOE has contracted with Energy and Environmental Analysis, Inc. over the last decade to examine automotive fuel economy. Typically, the previous analyses examined fuel economy in the context of regulatory requirements over a 10-year time horizon. The recent concerns, however, have extended the time horizon of interest, and this report addresses potential fuel economy in 2010.

This report builds off a previous EEA analysis for the DOE on fuel economy potential to 2001. As with the previous work, this effort has been cofunded by Energy, Mines and Resources Canada and the U.S. EPA. Although the analysis for those organizations utilize the same data base and methodology as the one employed in this report, the focus and results are slightly different due to differences in input assumptions employed.

The methodology utilized by EEA to derive fuel economy projections based on technological improvements was developed under contract to the U.S. Department of Energy, and relies on starting from a known vehicle technology and fuel economy baseline. The effects of various improvements to cars are estimated cumulatively from this baseline. As a result, the forecast for 2010 requires knowledge of improvements in the intermediate time frames of 1995 and 2001. Due to the current Congressional interest in fuel economy, the EEA forecasts for 1995 and 2001 have received considerable attention. The cumulative nature of improvements makes it important to forecast benefits for these years as accurately as possible. Over the last six months, EEA has engaged in dialogue with auto manufacturers, and, as a result of their critique, modified the

1995/2001 forecasts recently. These modifications are documented in Section 2.

The current methodology utilized by EEA to calculate fuel economy is based on a "linearized" approach that is an approximation of the exact engineering equations governing vehicle technology and fuel economy. While this approximation is adequate for the near term, it was believed that it would be inaccurate at levels that are double today's fuel economy values. A modified method that incorporates the exact engineering equations was devised, and is documented in Section 3.

Section 4 represents the main body of work for this forecast, describing technologies available for improving fuel economy in the post-2000 time frame. The information was derived from meetings with major Japanese and European manufacturers, who gave EEA considerable assistance with this project. The technologies and their characteristics are documented in extensive detail in this report.

Section 5 represents the analytical forecast of fuel economy for 2010 that utilizes the information in Section 4 within the methodology described in Section 3. Obviously, fuel economy forecasts for 2010 are subject to considerable technological and economic uncertainty. This is reflected in a scenario approach that defines differing supply curves of fuel economy under varying degrees of risk. The information is presented to allow independent trade-off in vehicle attributes or costs to attain high levels of fuel economy.

2. REVISED FORECAST OF FUEL ECONOMY FOR 1995/2001

2.1 METHODOLOGY

In order to forecast future fuel economy of individual vehicles or vehicle types, EEA has developed a methodology that relies on three steps:

- Specification of a baseline of fuel economy and vehicle technology attributes.
- Identification of individual fuel economy technologies applicable to each vehicle type and fuel economy benefits associated with these technological improvements.
- Adoption of technologies as dictated by synergistic and non-additivity constraints to attain different levels of fuel economy.

The methodology was developed by EEA over the last 10 years under contract to the U.S. DOE, and has received extensive public review. A key aspect of the methodology is the assumption that a vehicle's fuel economy can be estimated with reasonable accuracy if its attributes such as weight and performance (horsepower) are known, and the technologies embodied in the engine and trans mission are identified. The implication of this view of fuel economy is that different manufacturers building similar cars with similar technologies can reach nearly identical fuel economy levels in a given market segment. In fact, examination of the current car models available and their fuel economy levels suggest that, for a given level of technology, fuel economy within market segments is almost independent of manufacturer. Of course, some manufacturers have introduced more technology into the market place than others and, hence, are ahead in fuel economy.

This methodology was utilized to forecast fuel economy to 2001 for the three domestic manufacturers, in a joint contract for DOE and EMR, Canada.* The task report received considerable attention in the U.S. and was used as one of the documents forming the basis for new legislation. As a result, it was subject to detailed review by the domestic manufacturers and the forecasts were critiqued. EEA held discussions with the manufacturers, and utilized their inputs to revise some of the fuel economy benefits associated with each technology. The purpose of this section is to review the changes that have been made since the draft report was circulated, and revise the forecasts of fuel economy. The analysis does not utilize the new methodology for calculation of fuel economy developed in Section 3.

2.2 TECHNOLOGY UPDATE

An extensive list of technologies has already been compiled by EEA, and their fuel economy benefits estimated from a combination of sources including research papers, actual benefits from a few vehicles already featuring this technology, and from manufacturer submissions to DOT. As noted, the technology benefit estimates have attracted considerable attention from the auto-manufacturers, and the technology benefit estimates extensively critiqued.

EEA has examined the manufacturers critiques and has publicly defended its estimates. In brief, manufacturer critiques were based on:

- Use of incorrect baselines
- Misunderstanding of technology definitions
- Lack of control for performance and interior volume

A comprehensive list of technologies that can be used to improve fuel economy over the next 10 years is provided in Table 2-1. Technology costs and

---

* EEA "Domestic Manufacturers' Fuel Economy Capability to 2001, An Update" Draft Report to Martin Marietta Energy Systems, October 1989.

TABLE 2-1

TECHNOLOGY DEFINITIONS

Technology		Fuel Economy Baseline
Front Wheel Drive	-	Benefits include effect of weight reduction and engine size reduction starting from a late-1970's rear-wheel drive vintage design.
Drag Reduction I	-	Based on C_D decreasing from 0.375 in 1987 to 0.335 in 1995, on average.
Drag Reduction II	-	Based on C_D decreasing from 0.335 to 0.30 in 2001, on average.
Torque Converter Lock-up	-	Lock-up in gear 2-3-4 compared to open converter.
4-Speed Auto Transmission	-	3-speed auto transmission at same performance level.
Electronic Transmission Control	-	Over hydraulic system, with control of shift schedule and lock-up of torque converter.
Accessory Improvements	-	Improvements to power steering pump, alternator, and water pump
Lubricants	-	5W/30 replacing 10W-40 oil plus synthetic axle lubricants.

TABLE 2-1

TECHNOLOGY DEFINITIONS

(Continued)

Technology		Fuel Economy Baseline
Overhead Camshaft	-	OHV engine of 40 BHP/liter replaced by OHC engine of 50 BHP/liter but with smaller displacement for constant performance.
Roller Cam Followers	-	Over sliding contact follower.
Low Friction Pistons/Rings	-	Over 1987 base except for select engines already incorporating improvement.
Throttle Body Fuel Injection	-	Over carburetor (includes air pump elimination effect).
Multi-Point Fuel Injection	-	Over carburetor. Includes effect of tuned intake manifold, sequential injection and reduced axle ratio for constant performance.
4-Valve Engine (OHC/DOHC)	-	Over two-valve OHC engine of equal power. Includes effect of displacement reduction and compression ratio increase for 9.0 to 10.0.
Tires	-	Over 1987 tires, due to improved construction.
Intake Valve Control	-	Lift and Phase Control for intake valves, at constant engine output.

benefits are directly dependent on what a particular technology is being compared against. For example, the benefit of multi-point fuel injection is dependent on whether the comparison is against a carburetor or against throttle-body fuel injection. The comparison baseline for each technology is documented in Table 2-1. A second factor that has caused some misunderstanding in public reviews is a semantic issue, when a specific technology name designation represents a group of technologies. The introduction of certain technologies allow other changes to be made to a vehicle that contribute to a greater change in fuel economy than if it were introduced without other changes.

EEA's technology name designations include an entire group of technological changes for estimating technology benefits for certain technologies. For example, EEA's "Front Wheel Drive" technology benefit is based on the fact that the transverse engine location allows considerable exterior size reduction and accompanying weight reduction while keeping interior room constant. The secondary effects include engine downsizing to keep performance constant. Thus, the benefits associated with the term "Front-Wheel Drive" <u>includes</u> all of these primary and secondary effects. Similarly, the benefits for "overhead cam" engines is based on the fact that existing overhead valve engines have low specific output, and a new overhead cam engine of <u>lower</u> displacement can be used to replace the older engine while providing equal performance. The central variables that are <u>maintained constant over time are the interior volume of the car as well as the performance</u> as defined by its acceleration capability. These issues are of importance since it is the most common source of misunderstanding of the EEA technology benefit estimates.

While EEA's technology estimates have been documented in several reports to the Department of Energy, the recent interchange with manufacturers has led to some revisions to the benefit estimates. The fuel economy benefit (in percent) estimates were revised upward or downward, based on manufacturer inputs or available measurements, as follows:

• Roller Cam Followers	-	Increased from 1.5 to 2.0 percent
• Continuously Variable Transmission	-	Increased from 2.5 to 3.5 percent
• Drag Reduction for Large Cars (Segment 6)	-	C_D reduced by 20 percent from 0.43 to 0.34
• Electronic Transmission Control	-	Decreased from 1.5 to 0.5 percent
• Accessory Improvements	-	Decreased from 1.0 to 0.5 percent due to elimination of 2-speed accessory drives
• 4 cyl/4 valve replacing 6 cyl/2 valve engine	-	Decreased from 10 to 8 percent

In addition to the specific changes listed above, the overhead cam (OHC) to overhead valve (OHC) engine benefit estimate was revised to allow for a modern category of overhead valve engines that have appeared in the 1987-1990 time frame. Engines were classified on the basis of specific output as being "old OHV", "advanced OHV", "old OHC" and "new OHC". The fuel efficiency benefit and the specific output characteristics associated with each engine type are as follows:

Engine Type	Specific Output (Car) (bhp/L)	Benefit (%)
Old OHV	35 to 37	Base
Advanced OHV	44 to 46	+3
Old OHC	44 to 46	+4.5
New OHC	50+	+6.0

Finally, some engines were recognized for having already adopted the first round of friction reduction by 1988. These engines are the GM 3800 V-6, the Quad 4, the Ford 1.9L and the Ford 3.0L engines. The recognition of these engines prevents double counting of friction reduction benefits.

A complete listing of the technological benefits used in the forecast is provided in Table 2-2. Two specific points are of great importance in considering these estimates. First, the estimates are relative to the technology baseline detailed in Table 2-1. Second, the benefit estimate is with constant performance and interior volume. These factors are paramount in determining the size of the benefit.

Separately, diesel engines and two stroke engines were not considered for 2001 analysis, principally because it appears that a 0.4 g/mi NO_x standard is virtually certain for the mid-1990's in the U.S. Neither engine has demonstrated a capability to meet this standard, and was deemed too risky for inclusion by 2001. This assumption is unchanged from the one used in the previous report.

2.3 REVISED FORECASTS FOR 2001

The years of concern for the earlier analysis are 1995 and 2001. For each year, two scenarios have been developed. The first is a product plan based scenario that attempts to forecast what will happen in the absence of new fuel economy regulations. EEA analysis has revealed that technologies that are available and cost effective are generally adopted by manufacturers as part of the product plan. Here, the term "cost-effectiveness" is based on the incremental price of the technology being lower than the cost of fuel saved over 4 years (50,000 miles for cars and 60,000 miles for trucks). In addition, product plans are often revealed in the trade press and are tracked by EEA to the extent available. The cost-effectiveness criterion is used to estimate if a technology will be included in the product plan at a specified fuel price.

All of the technology analysis is based on maintaining constant interior volume and constant performance. A review of the product plans and actual events between 1988 and 1990 show that this assumption does not hold as cars are increasing in size within market segments and offering improved

TABLE 2-2

TECHNOLOGICAL BENEFIT

ESTIMATES UTILIZED

Technology	F/E Benefit (%)*	Comment
Front Wheel Drive	10 5	over 1970's RWD vehicles over 1980's RWD vehicles
Drag Reduction	2.3	per 10 percent C_D reduction
4-speed Auto Transmission	4.5	Widely used in 1988
Torque Converter Lock-up	3.0	Widely used in 1988
5-speed Auto Transmission	2.5	Over 4-speed auto transmission
6-speed Manual Transmission	2.0	Over 5-speed manual
Electronic Transmission Control	0.5	For auto transmission only
CVT	3.5	For mini and subcompact cars only
Accessories	-0.5	Varies between 0.3 and 0.7, depending on market class
Oil (5W-30)	0.5	Already used in some large cars
Advanced Tires	0.5	--

TABLE 2-2

TECHNOLOGICAL BENEFIT

ESTIMATES UTILIZED

(Continued)

Technology	F/E Benefit (%)	Comment
Throttle-Body Fuel Injection	3	Widely used
Multi-Point Fuel Injection	6	Widely used
Advanced OHV Engine	3	Over old OHV design
Modern OHC Engine	6	Over old OHV design
Roller Cam Followers	2	Widely used in domestic cars
Friction Reduction I	2	Except for specific engines
Friction Reduction II	2	Post 1995 technology
4 cyl/4 valve over 4 cyl/2 valve engine	5	At constant performance
4 cyl/4 valve over 6 cyl/2 valve engine	8	At constant performance
Intake Valve Control	6	Synergistic affects with 5-speed auto/CVT
Electric Power Steering segments	1	Only for cars in market segments 1, 2 and 4

performance. Examples of such events that have already occurred since 1988 include:

- Ford's 1989 Thunderbird/Cougar is larger and 400 lbs heavier than its predecessor.
- GM's new intermediate GM-10 body (Chevy Lumina) is eight inches longer, 300 lbs heavier and 15 HP more powerful than the A-body vehicles that it replaces.
- Chrysler's 1990 New Yorker has been "stretched" and is 250 lb heavier than the 1989 version.

New products in the future are expected to continue these trends. However, the simultaneous introduction of new technology results in no net reduction (or an improvement) in new car fuel economy even after weight increases and performance enhancements have been accounted for.

One aspect to be considered for the 1995 model year is the lead time requirement. The 1995 model year is now only about four years away, and most of the products have already been designed for this date. As a result, the 1995 analysis includes all of the known increases in performance, size and luxury that have already occurred since 1988 or will occur shortly, since these cannot now be changed.

The lead time constraints are also instrumental in preventing any significant increases in fuel economy by 1995. Manufacturers can make marginal improvements over those already planned for 1995 by accelerating (or "pulling ahead") technologies planned for introduction in 1996/97 and by extending the market penetration of technologies that are used in parts (but not all) of its product line. Among the technologies that can be pulled ahead are:

- Increased use of overhead cam engines in some domestic cars/trucks
- Increased use of roller cam followers in import cars/trucks
- Increased use of four-speed auto transmissions
- Increased penetration of 5W-30 oil and improved tires

- Complete conversion to multi-point fuel injection with tuned intake manifolds.

The limited flexibility for 1995 can lead to a maximum fuel economy improvement over the product plan case of only about 0.5 to 2.0 MPG, depending on the market segment.

For 2001, such restrictions are less applicable. The product plan case holds attributes constant from 1995 as does the maximum technology scenario. (Of course, size class shifting is considered separately, and these observations are for a given market class). It can be argued that attributes <u>within</u> market class can be reduced, and performance reductions can also be considered beyond the technology improvements. Size reductions are <u>not considered within market class</u> because the classes are narrowly defined in terms of passenger volume. Thus, any significant shrinkage within market class is equivalent to a market class sales shift. Although all classes have increased in size, a new market class of minicompacts has emerged with the size of the older subcompacts. As a result, the forecast implies no loss of consumer choice of available model sizes. However, performance is reduced in the sports and luxury classes relative to the baseline.

The maximum technology scenario considered in this analysis is, indeed, a real <u>maximum</u>. Many automanufacturers contend that the level of change forecast is too difficult given the other challenges in the safety and environmental arena. As a result, it is possible that the 2001 maximum technology case will be actually attained only in 2005. The scenario envisages that <u>all</u> products are redesigned employing new materials such as aluminum and advanced plastics extensively, and that the only engines sold are multi-valve small displacement engines with intake valve control in virtually all but the smallest cars. The extent of such changes would impose a heavy burden of retooling for the industry and would require unprecedented and risky changes to every product sold. These factors should be understood when considering the maximum technology scenario results.

2.4 RESULTS

Table 2-3(a) shows the computations of benefits in percent while holding size and performance constant at 1987 levels. As can be seen, technology benefit revisions largely offset each other, and the net benefit declines only slightly from 16.06 percent forecast earlier, to 15.66 percent. Of course size and performance are increasing and there effects are included in Table 2-3(b). The new addition to this table is the effect of new safety and emission standards that are expected in the 1987-1995 time frame. The standards are expected to result in a 3 percent decline in fuel economy.

Forecasts for 2001 are shown in Table 2-4 for two scenarios. In the "product plan" scenario, it is assumed that performance, size and luxury peak out in 1995, and remain stable beyond that point. In the "maximum technology" scenario, performance size and luxury are held constant at 1987 levels. Both product plan and maximum technology scenarios show lower MPG values but almost half of the decline can be traced to the 0.8 MPG penalty for new safety/ emission standards not considered earlier. However, if fuel prices increase as anticipated, there will be a change in vehicle sales mix favoring fuel economy.

TABLE 2-3 (a)

REVISED PROJECTION

U.S. DOMESTIC MANUFACTURERS

1995 PRODUCT PLAN CASE

Technology	F/E Gain (%)	Penetration Increase from 1987 (%)	1995 Penetration	Fleet F/E Gain
Front Wheel Drive	10.0	12	86	1.20
Drag Reduction (C_D ~0.33)	2.3/4.6**	65/15	~100	2.19
4-speed Automatic Transmission	4.5	40	80	1.80
Torque Converter Lock-up	3.0	20	80	0.60
Electronic Transmission Control	0.5	80	80	0.40
Accessory Improvements	0.5	80	N/M	0.40
Lubricant/Tire Improvements	1.0	100	100	1.00
Engine Improvements				
- Advanced Pushrod	3.0	(40)	(30)	1.20
- Overhead Camshaft	3.0	45	69	1.35
- Roller Cam Followers	2.0	40	95	0.80
- Low Friction Pistons/Rings	2.0	80	100	1.60
- Throttle Body FI	3.0	12	40	0.36
- Multi-point FI (over throttle body)	3.0	12	60	0.36
4 valves per cylinder engine				
- 4 cylinder replacing 6*	8.0	180	18	1.44
- 6 cylinder replacing 8*	8.0	120	12	0.96
Total F/E Benefit				15.66

* 1987 distribution: 20.5% V-8, 29.5% V-6, 50% 4 cylinder

** Drag reduction for large/luxury cars from C_D = 0.42 baseline.

TABLE 2-3(b)
1995 PRODUCT PLAN
U.S. DOMESTIC LDV FLEET

1987 Fuel Economy:	26.7 MPG
1995 Fuel Economy w/o size or peformance increase	30.9 MPG
Size/weight Increase	-1.4 MPG
Performance Increase	-0.7 MPG
Effect of Emission/Safety Standards	-0.8 MPG
1995 Product Plan F/E	28.0 MPG

TABLE 2-4
REVISED PROJECTION
POTENTIAL U.S. FUEL ECONOMY IN 2001 UNDER ALTERNATIVE SCENARIOS

	Fuel Economy Benefit	Product Plan Mkt. Pen 1995 - 2001	Product Plan F/E 1995 - 2001	Max. Technology Mkt. Pen 1995 - 2001	Max. Technology F/E 1995 - 2001
Weight Reduction	3.3/6.6	100	3.30	100	5.28
Drag Reduction	1.15/2.3	80	0.92	80	1.84
Intake Valve Control[1/]	6.0	30	1.80	70	4.20
Overhead Cam Engines	3.0	30	.09	30	.90
6 cyl./4V replacing 8 cyl.	8.0	4	0.32	8	0.64
4 cyl./4V replacing 6 cyl.	8.0	6	0.48	12	0.96
4 cyl./4V replacing 4 cyl.	5.0	20	0.50	50	2.50
Multi-point fuel injection (over TBI)	3.0	40	1.20	40	1.20
Front wheel drive	10.0	5	0.50	13	1.30
5-speed auto. transmission*	2.5	20	0.50	40	1.00
Continuously variable transmission*	2.5	20	0.50	40	1.00
Advanced engine friction reduction	2.0	100	2.00	100	2.00
Electric Power Steering	1.0	5	0.05	30	0.30
Tire Improvements	0.5	20	0.10	100	0.50
Total F/E Benefit (%)			12.47**		22.22**
Unadjusted CAFE (MPG)			31.5		36.8

Note: Product plan scenario starts from a different 1995 base than the maximum technology scenario which holds performance and size constant at 1987 levels.

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* Over 4-speed auto transmission with lock-up.

** Synergy of intake valve control with 5-speed/CVT transmissions results in a loss of 2 percent in fuel economy.

REFERENCES FOR SECTION 2

1. Gino Sovran and Mark S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule", SAE Paper 810184, February 1981.

2. Gino Sovran, "Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Cycle", SAE Paper 830304.

3. CALCULATION PROCEDURE REVISIONS FOR FUEL ECONOMY ESTIMATION

3.1 OVERVIEW

All of the analysis from 1995 and 2001 involved a relatively simple method for forecasting fuel economy. Technology benefits were derived as additive percentage changes in fuel economy with synergy and non-additivity handled exogenously (as adjustments to the individual factors) to account for such effects. It can be easily seen that the additive method is more conservative than the multiplicative method, since

$$1 + \Sigma r_i < \Pi (1 + r_i)$$

where r_i is the individual technology benefit. This is because all of the second order terms in the products are positive, giving rise to a greater benefit estimate than the estimate derived using the additive method.

In reality, the situation is more complex since many factors affecting fuel economy such as weight reduction, drag reduction, etc. do cause additive benefits. Other technologies, such as engine thermal efficiency increases and reduction in drivetrain loss, produce multiplicative benefits. As a result, neither method yields accurate results, but the differences are small when benefits of each technology are below 10 percent. In order to resolve the problem of an overly conservative prediction, the method utilized historically by EEA was to update the "baseline" from which benefits are calculated over the period of a product cycle. Each time a new car model is brought out with a package of technologies, the new vehicle MPG becomes the "baseline" from which MPG effects are calculated in the EEA model. This method minimizes error by not having to refer back to a (non-existent) base year model for technology benefit calculations, and results in a better approximation of the actual engineering effect.

Clearly, the method is an approximation to make the calculations relatively simple, yet yields results that have been accurate to ±0.2 MPG, historically.

In projecting a maximum technology boundary case to the post-2000 time frame it was believed that these approximations could cause larger errors and a more rigorous engineering model was required. The model is described below.

3.2 ENGINEERING MODEL

The model follows the work of Sovran[1/2/] who produced a detailed analysis of tractive energy requirements on the EPA fuel economy test schedule, i.e., the city cycle and the highway cycle. Each driving cycle specifies speed as a function of time. The force required to move the vehicle over the driving cycle is easily derived from the Newton's laws of motion:

$$F = M\, dv/dt + R + D$$

where F = the force required

M = the vehicle mass

dv/dt = the acceleration rate

R = the tire rolling resistance

D = the drag force

By simple algebraic manipulation it can be shown that:

$$F = M dv/dt + gMC_R + C_D \varrho \frac{A\ V^2}{2} \quad \text{-- (1)}$$

where C_R is the rolling resistance co-efficient

C_D is the drag coefficient

g, ϱ are the gravitational acceleration and air density respectively.

Since V is specified as V(t), and the energy required is the integral of

$$E = F.\ ds$$
$$= F.\ v.\ dt.$$

In the car, energy is provided only when F is greater than zero, while energy during deceleration is simply lost to the brakes. Taking these factors into account, Sovran and Bohn[2/] showed that energy per unit distance (S)

$$E/S = \alpha MC_R + \beta\ C_D A + \delta M \text{ --- (2)}$$

where α, β and δ are constants virtually independent of vehicle characteristics, but are different for the city and highway cycle. In essence, each term represents one component of the total force, the first representing energy to overcome tire rolling resistance, E_R, the second to overcome aerodynamic drag, E_A, and the third to supply kinetic energy of acceleration, E_k. In the absence of acceleration (during steady speeds) E_k is zero. Figure 3-1 shows the drag and the rolling resistance forces for a typical car at steady state cruise, as well as the driveline loss described below.

Sovran[1/] also related tractive energy to fuel consumption by adding the work required to drive accessories, and the energy wasted by the engine during idle and braking. He defined the average engine brake specific fuel consumption over the test cycle as bsfc, and derived the following equation

$$FC = \frac{bsfc}{\eta_d} [E_r + E_A + E_k] + bsfc\ E_{AC} + G_i\ (t_i + t_b) \quad . \ . \ . \ . \qquad (3)$$

where η_d is the drive train efficiency

E_{AC} is the accessory energy consumption

G_i the idle fuel consumption rate

t_i, t_b the time at idle and braking in the test cycle.

The above equation shows that reductions in rolling resistance, mass, drag and accessory energy consumption, and idle fuel consumption cause <u>additive</u> reductions in fuel consumption.

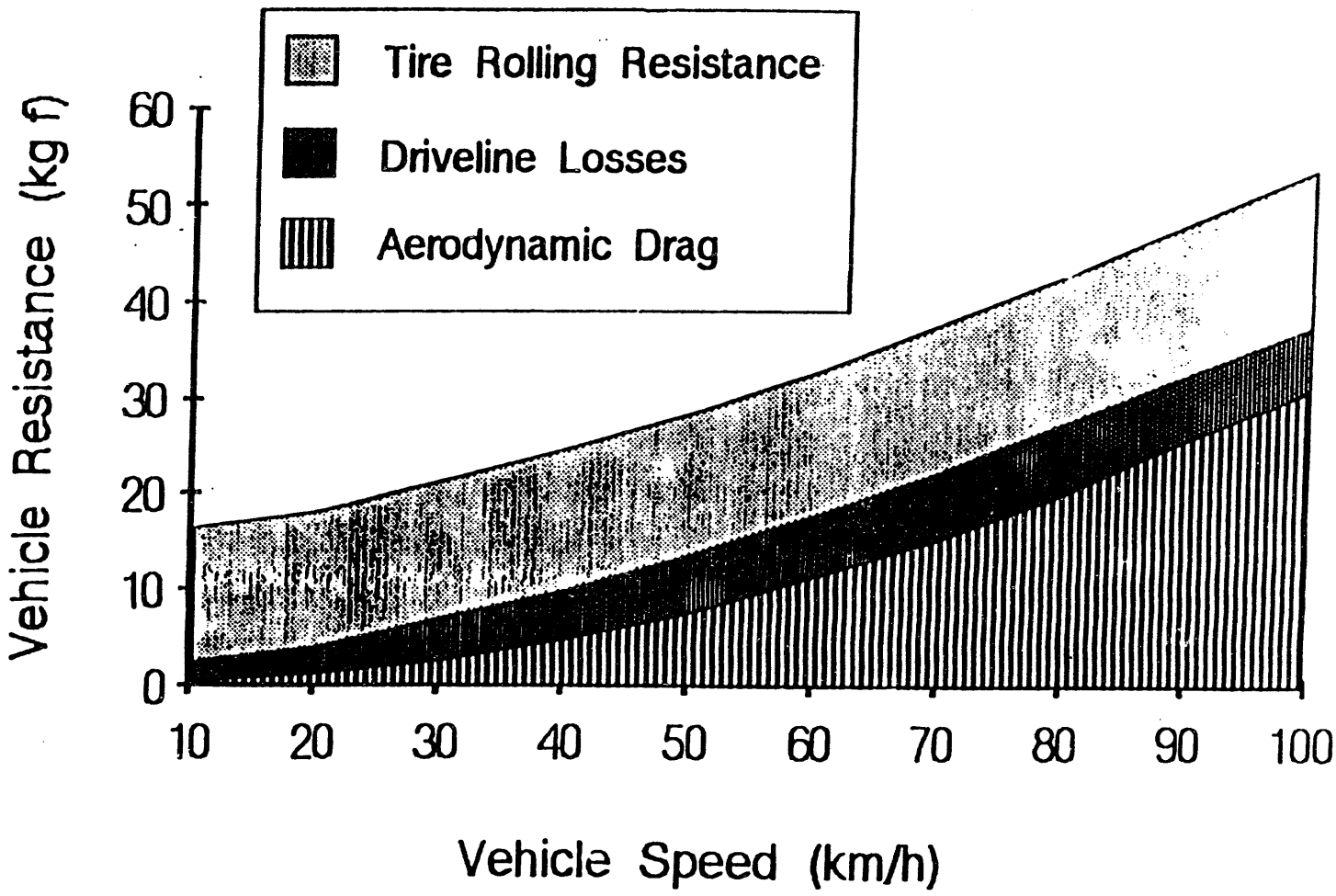
The engine output energy is supplied to match the tractive energy requirements. If total energy required is defined as

$$E = \frac{1}{\eta_d} [E_A + E_R + E_k] + E_{AC} \quad . \ . \ . \qquad (4)$$

then $E = \overline{BHP}.t$ (engine power output)

FIGURE 3-1

Vehicle Resistance in Coastdown Test



Engine output power can be further decomposed to provide explicit recognition of engine internal losses. There are no conventions regarding the nomenclature of such losses. In general, the engine has two types of losses, one arising from the thermodynamic efficiency, η_T, of combustion and heat recovery, and the second due to friction, both mechanical and aerodynamic. Aerodynamic friction is more usually referred to as pumping loss. A third component that is sometimes excluded from the engine efficiency equation is the power required to drive some internal accessories such as the oil pump and the distributor. Items such as the water pump, alternator and fan are usually (though not always) classified under accessory power requirements. In this analysis, power for all accessories - both internal and external - are classified under accessory power requirements and the following relationship holds:

$$BHP = IHP \cdot (1 - P - F_r) \quad . \; . \; . \qquad (5)$$

Where IHP is indicated horsepower

P is the pumping loss fraction

F_r is the mechanical friction loss fraction

Since fuel consumption, FC, can be written in terms of brake specific or indicated specific fuel consumption,

$$FC = \overline{bsfc} \cdot BHP \cdot t = \overline{isfc} \cdot IHP \cdot t = k \; . \; IHP . t/\eta_T$$

$$\overline{bsfc} = \frac{\overline{isfc}}{(1-P-Fr)} \quad . \; . \; . \qquad (6)$$

Substituting equation (6) into (3) we obtain

$$\eta_d \; FC = \frac{\overline{isfc}}{1-P-F_r} [E_R + E_A + E_k + \eta_d \; E_{ac}] + G_i \; [t_\lambda + t_b] \quad . \; . \; . \qquad (7)$$

The isfc is principally a function of combustion chamber design and compression ratio of the engine, and to a lesser degree, the air fuel ratio. Since nearly all cars operate at stoichiometry, the air fuel ratio is currently not a factor but could become one if "lean-burn" concepts are utilized.

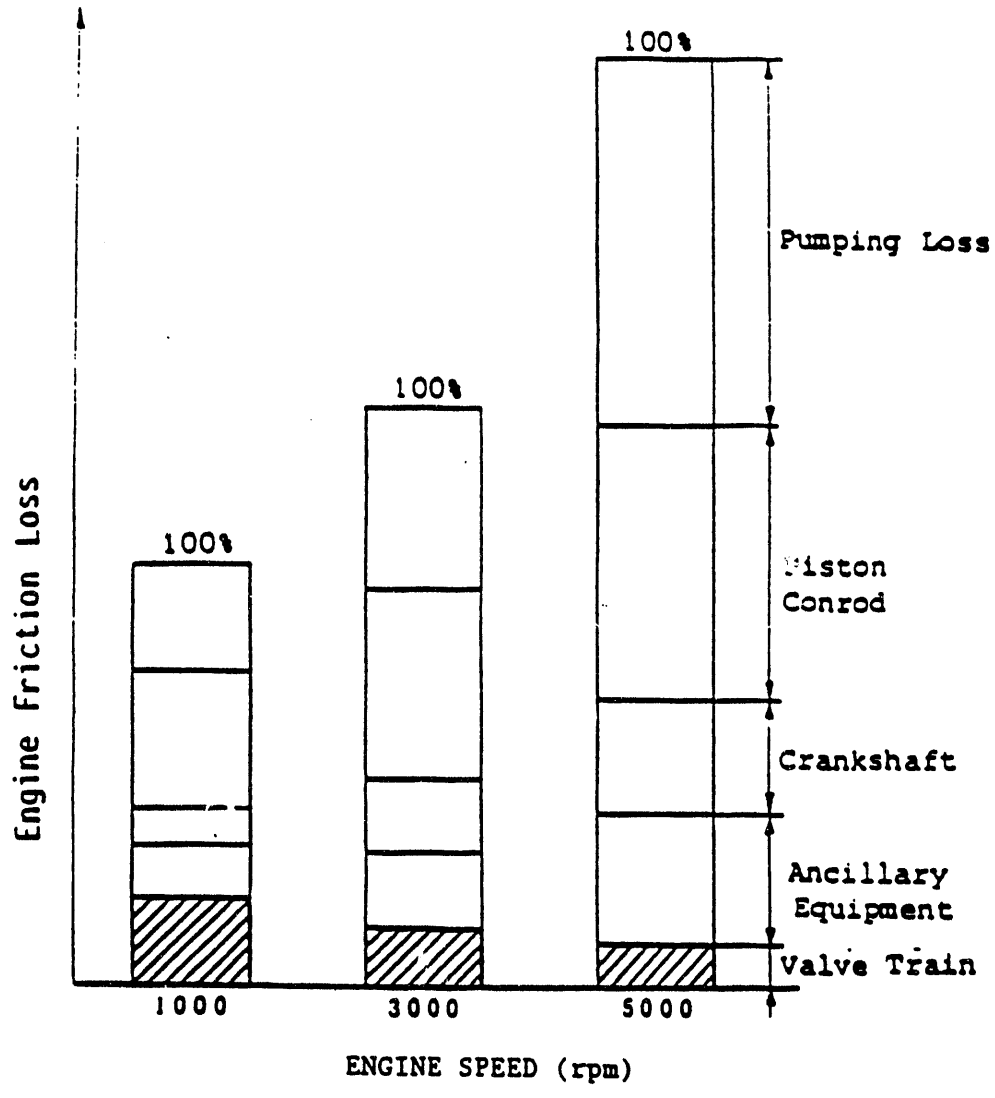
Pumping losses are dependent principally on the relative load of the engine over the cycle. The larger the engine for a given car weight, the lower the load factor and the higher the pumping loss due to throttling. Pumping losses are also incurred in the intake and exhaust manifolds and valve orifice. The use of tuned intake and exhaust manifolds, and greater valve area (e.g. by utilizing 4 valves/cylinder) reduce pumping losses. Losses other than throttling loss are not unimportant in the contribution to overall pumping loss.

Engine mechanical friction is associated with the valve train losses, piston and connecting rod friction, as well as the crankshaft friction. At low RPM, valve train friction is quite large as a percent of total friction, but decreases at higher RPM, while piston/connecting rod friction increases rapidly with increasing RPM. Total engine friction increases non-linearly with engine RPM.

Idle fuel consumption is also affected by changes in engine parameters. At idle, all of the fuel energy goes into driving the accessories and overcoming pumping and friction loss, since there is no output energy requirement. Hence, decreases in pumping loss or mechanical friction result in much larger percentage reduction in fuel consumption at idle than at load.

Mitsubishi provided data on the general components of friction of the engine as shown in Figure 3-2. The pumping loss shown here is due to internal airflow and not due to throttling. At closed throttle idle pumping loss is approximately equal to frictional loss. Mitsubishi also provided data on the effect of reducing valve train friction on fuel consumption at various speeds. As can be seen in Figure 3-3, the effect is very large at idle, over three times the effect at 100 km/hr cruise.

FIGURE 3-2

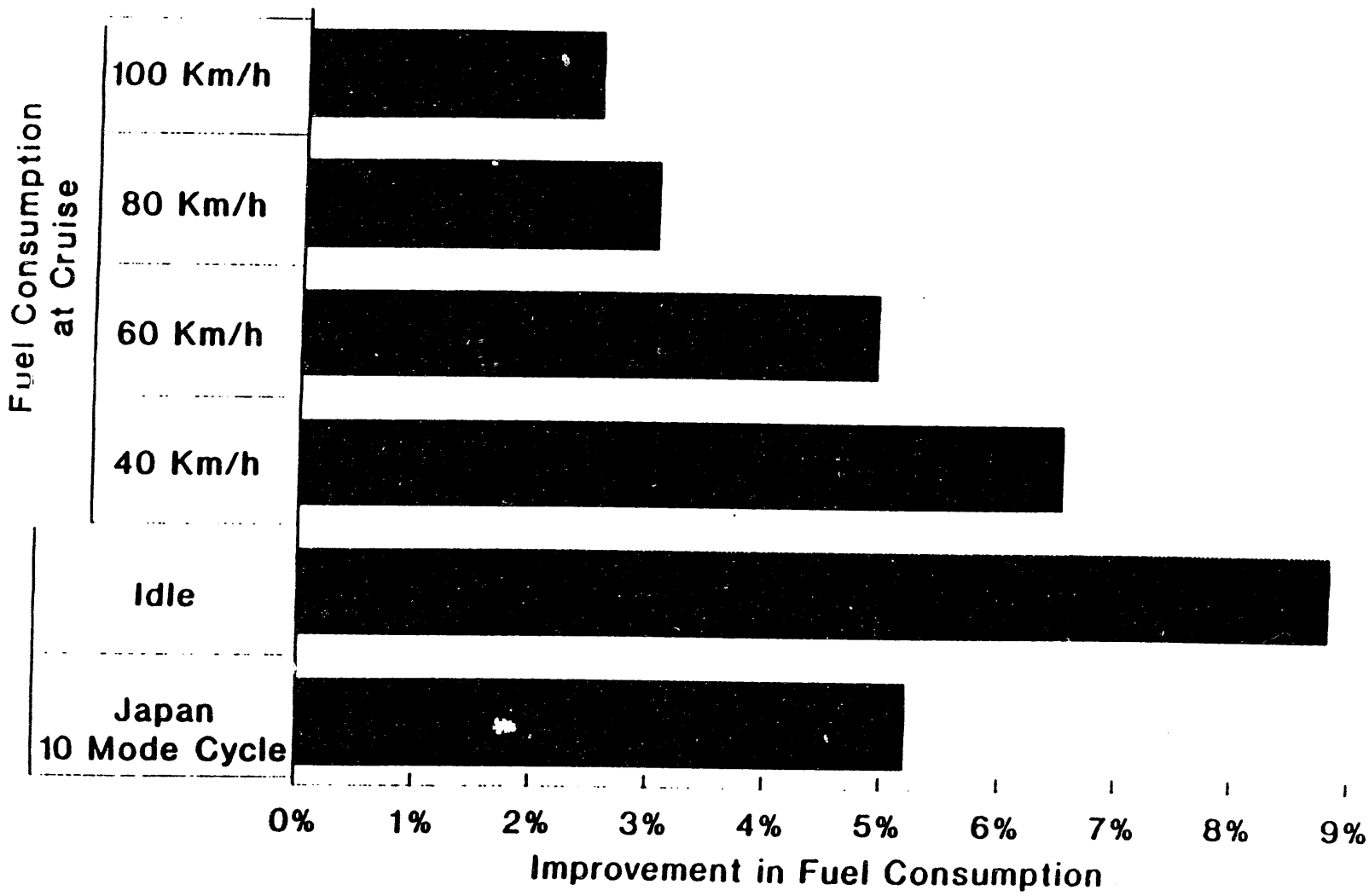


PROPORTION OF ENGINE FRICTION DUE TO VALVE TRAIN

SOURCE: Mitsubishi

FIGURE 3-3

Improvement in Fuel Consumption Due to Needle Bearing Roller Type Rocker Arm



Equation 7 also shows the general structure of the calculation procedure. A simple differentiation of (7) yields:

$$\frac{dFC}{FC} = \frac{d\eta_T}{\eta_T} + \frac{P}{(1-P-F_r)\eta_d}\frac{dP}{P} + \frac{F_r}{(1-P-F_r)\eta_d}\frac{dF_r}{F_r}$$

$$+ \frac{E_A}{E_A+E_R+E_k+\eta_d E_{AC}}\frac{dE_A}{E_A} + \ldots + \ldots \qquad (8)$$

where each derivative is expressed as a percentage change. Thus, a one percent change in thermal efficiency translates to a one percent change in fuel economy, but a one percent change in pumping loss must be weighted by the fraction that pumping loss is of total output energy. Similarly, aerodynamic tractive energy change must be weighted by the fraction that aerodynamic energy loss is of total tractive energy.

Two observations are required at this point. First, equation (8) assumes that the vehicle can be reoptimized for any change, so that engine variables are not affected by tractive energy requirements. As pointed out by Sovran, this is not always possible. For example, aerodynamic losses are near zero at low speed but high at high speed. Hence, an engine cannot be simply downsized as aerodynamic loss is reduced, since the smaller engine will not have enough power at low speed. As a result, a higher gear must be added along with engine downsizing to achieve a correct compromise. In theory, it is possible to reoptimize the entire drivetrain, but in practice, compromises cause significant losses in fuel economy from the attainable maximum. In the long run, as for 2010, some factors can indeed be optimized to yield the full predicted value, while other factors cannot. For example, it appears unlikely that predicted engine friction reduction related fuel savings can be obtained even by using appropriate wide ratio transmissions. On the other hand, rolling resistance decreases may provide the predicted fuel savings as its effect is felt uniformly throughout the speed range. Second, the differential

form in (8) is useful only for small changes in any of the variables (less than 10 percent) and equation (7) should be used for larger changes.

3.3 REVISED CALCULATION PROCEDURE

Methods to increase the fuel economy (reduce fuel consumption) must rely on reduction of energy contributed by each of the terms shown in Equation (7). Equation (8) is useful only if the change in factors is small, but not applicable for the large changes. Focusing on the terms in equation (7) it is easily seen that fuel consumption is decreased by:

- decreasing friction and pumping loss
- decreasing weight
- decreasing drag
- decreasing rolling resistance
- decreasing accessory power consumption
- decreasing idle fuel consumption

Of course, a given technology can act on more than one of these factors simultaneously. Table 3-1 shows the relationships between individual technologies and the terms listed in equation (7). Drivetrain efficiency, η_d is <u>not</u> the major factor in the benefits associated with multi speed transmissions; rather, the reductions in pumping and frictional losses are the biggest factor. It should also be noted that most engine improvements affect idle fuel consumption, so that idle consumption can be approximated as:

$$FC = \frac{\bar{isfc} \quad [E_R + E_A + E_K + \eta_d (E_{AC} + E_I)]}{\eta_d \, [1-P-F_r]} \quad . \; . \; . \qquad (9)$$

Where E_I is an "equivalent" energy at idle to drive the accessories and torque converter. E_I is simply a mathematical artifact to make the analysis simpler for forecasting.

TABLE 3-1

TECHNOLOGY/ENERGY USE RELATIONSHIP

	ISFC	P	F_r	E_A	E_R	E_K	E_{AC}	G_i	η_d
Weight Reduction					✓	✓			
Drag Reduction				✓					
4-speed Automatic		✓	✓						✓
TCLU								✓	
Electronic Trans Control		✓	✓						
Accessory Improvements							✓		
Tires improvement					✓				
5W-30 oil			✓						
Overhead cam	✓	✓	✓					✓	
Roller Cam Followers			✓					✓	
Low Friction Piston/Rings			✓					✓	
Fuel Injection	✓	✓						✓	
4-valves/cylinder	✓	✓						✓	
Intake Valve Control		✓						✓	
5-speed Automatic		✓	✓						
Electric Power Steering							✓		

The relationship between fuel consumption and vehicle variables can be derived from equation 7 in exact terms if the co-efficients are evaluated for the FTP and HIGHWAY driving cycles. In fact, Sovran utilized a detailed evaluation of these cycles to derive the sensitivity of fuel consumption to vehicle weight, aerodynamic drag and tire rolling resistance coefficient. The general characteristics of the two cycles are shown in Table 3-2. One striking factor is that nearly 41 percent of the time on the FTP is spent in deceleration or at idle. In comparison, less than 10 percent of the time on the highway cycle is spent in braking or at idle. This difference, coupled with the different speeds and average acceleration rates in each cycle, leads to substantially different sensitivities between the two cycles.

In order to evaluate the sensitivity of fuel consumption to changes in vehicle parameters, information is required on the fuel consumption at idle and braking as well as the fuel consumed by driving accessory loads. Sovran utilized data on 1979/1980 GM cars and found that idle and braking fuel consumption was proportional to engine size. As an approximation, he assumed idle + braking consumption to be a constant fraction of total fuel consumed and estimated this fraction at 16 percent for the FTP and 2 percent for the highway cycle. He utilized a similar assumption for the accessory fuel consumption fraction, holding it constant at 10 and 9 percent respectively. This is equivalent to the approach in Equation (9) where the term $[E_{AC} + E_I] \cdot$ bsfc is replaced by a constant. Utilizing these assumptions, he derived sensitivity coefficients that were dependent on the drag to mass ratio and the rolling resistance coefficient. Using typical value for the average 1988 car, with a mass of 1400 kg (3100 lb), C_D of 0.37 frontal area of 1.9 m^2 and tire rolling resistance of 0.01, the fuel consumption sensitivity coefficients are as follows:

C_D = 0.28
Weight = 0.56
C_R = 0.24

TABLE 3-2

FUEL ECONOMY CYCLE CHARACTERISTICS

	Urban	Highway
Speed (average) kmh	38.4	77.6
Speed (max) kmh	91.5	96.8
Distance, km	12.0	16.5
Time at idle (s)	249	3
Time of braking (s)	311	57
Total time for cycle (s)	1373	765
Percent of time at idle and braking	40.8	9.84

These assume that the engine and drivetrain are adjusted to provide constant bsfc, a factor which may not be realized in practice. Second, the constants are dependent to a certain extent on the assumptions for the fraction of fuel consumed at idle + braking, and by accessory power demands. (The smaller these fractions, the larger the sensitivity coefficients).

Since Sovran's analysis relied on data from 1980 cars, it is useful to examin the changes that have occurred since that time. The biggest change is the fact that engine displacement has been reduced by a larger amount than weight reducing the fraction of fuel consumed at idle. The use of multipoint fuel injection coupled with deceleration fuel shutoff in many cars reduces it further. Accessory load may have also declined largely because the cooling fan has been replaced by the electric fan in front wheel drive cars, and the electric fan is turned on only on a "on-demand" basis. In addition, the othe accessories such as the alternator, the power steering pump and the water pum have been improved over the last decade. It is difficult to say whether the improvements have resulted in a decline in the percent of energy utilized by accessories since total vehicle fuel consumption has also declined significantly. Accessory drive energy may have been constant as a percentage of total energy use, at 10 percent.

As noted, it may be difficult to realize the full potential of aerodynamic drag reduction since engine sizing is dependent on low speed acceleration requirements where drag is not a factor. However, weight reduction which reduces E_K and E_R may allow a higher level of engine downsizing than projected largely because drag reduction has exceeded the level of weight reduction over the last 10 years, and its full energy use reduction potential not exploited. As a result, EEA anticipates that the predicted value for weight and rolling resistance sensitivity can be realized by 2010 whereas only 75 percent of drag reduction related efficiency benefit will be realized.

Sensitivity coefficients for the engine related variables can be similarly derived from equation (8). One area for which data is very limited is the fraction of indicated horsepower that is lost in pumping work and friction

over the composite cycle. In both cycles, average load factors at non-idle conditions are in the 0.25 to 0.35 range. EEA obtained limited data on P, the pumping loss fraction, and Fr, the friction loss fraction, and estimates for both variables were in the 0.2 to 0.25 range. Only one company provided confidential data showing that P was 0.18 and Fr was 0.21, for a vehicle with modern overhead cam (2-valve) engine, fuel injection, four-speed automatic transmission, and vehicle weight to horsepower ratio of 23 lb/hp. This indicates that 61 percent of indicated horsepower is translated to useful shaft horsepower over the cycle.

Using the conservative assumption that engine improvements improve bsfc and idle fuel consumption by the same amount, we obtain the following sensitivity coefficients:

Thermal efficiency	-	1.00
Friction reduction	-	0.344
Pumping loss	-	0.295

However friction reduction and pumping loss reduction cannot be completely translated to efficiency gains as suggested above. Friction benefits at low RPM do not yield as large an increase in horsepower as at high RPM due to non-linear rate that friction increases with RPM. The engineering consensus was that only 0.67 of the benefits could be recovered. Pumping loss, on the other hand, principally occurs due to throttling, and is less related to engine wide-open throttle horsepower. Hence, a larger amount of the theoretical benefit could be realized in actual practice. Again, an engineering estimate was that 80 percent of the theoretical benefit could be realized.

Table 3-3 provides a summary of the estimates of the EEA estimated sensitivity coefficients that may be attained in actual practice, as opposed to the estimates derived purely from equation (8). In the application of these coefficients, it should be recognized that they:

- apply to fuel consumption and not to fuel economy
- can be used only for small variations for any of the variables involved.

When large reductions of any variable are likely to occur the preferred form of analysis is to use equation (7) with a "slippage" factor to account for the fact that theoretical benefits cannot be attained in actual practice for some variables of concern.

TABLE 3-3

ESTIMATED FUEL CONSUMPTION SENSITIVITY COEFFICIENTS

Variable	FC Sensitivity*
Weight reduction	0.54 (0.64)**
Drag reduction (C_D)	0.22
C_R reduction	0.23
Thermal efficiency	1.00
Pumping loss	0.23
Friction loss	0.23
Drivetrain efficiency	0.78
Accessory power	0.10

* Percent reduction in fuel consumption per percent reduction in independent variable.

** Figure in parentheses includes effect of proportional reduction of displacement.

REFERENCES FOR SECTION 3

1. Gino Sovran and Mark S. Bohn, "Formulae for the Tractive Energy Requirements of Vehicles Driving the EPA Schedule", SAE Paper 810184, February 1981.

2. Gino Sovran, "Tractive-Energy-Based Formulae for the Impact of Aerodynamics on Fuel Economy Over the EPA Driving Cycle", SAE Paper 830304.

4. ADVANCED TECHNOLOGIES TO IMPROVE FUEL ECONOMY IN THE POST-2000 TIME FRAME

4.1 OVERVIEW

The term "advanced" is used to describe technology that could broadly become available in the 2001-2010 timeframe. As with technologies to be introduced in the 1990-2001 timeframe, each advanced technology could be introduced in the mid-to-late 1990's in some car models, but their total market penetration will be limited. At the other end of the time frame, it is likely that even by 2010, some cars will not feature all of the advanced technology. The technologies described below span the range of possible mechanisms to improve fuel economy, as defined in Section 3 of this report. Most of the information on these technologies came from detailed interviews with Toyota, Honda and Nissan in Japan and VW in Europe. These corporations provided both qualitative and quantitative inputs for the analysis. In addition, the trade press and SAE publications provided additional inputs into areas not covered in the auto indust meetings. The technology feasibility is judged in the context of prototypes that are displayed by manufacturers to showcase advanced technology.

For each technology, EEA has defined likely fuel economy benefit level for 2010 as a well as maximum possible level that represents the most optimistic view on each technology. The individual technologies and their specific benefits are noted in terms of their impact on the various contributors to energy consumption. Translation on these effects into a net fuel economy impact is considered in Section 5.

4.2 WEIGHT REDUCTION

In general, weight reduction can be achieved by two techniques.

- substitution of lighter, advanced materials.
- improved packaging efficiency by design improvements.

These processes have been occurring in new models throughout the 1980's, though the late-1980's has seen a reversal of the improved packaging efficiency trend.

In order to estimate the weight reduction possible by 2010 through the use of advanced materials, a detailed review of available literature was completed. The articles described the total weight reduction possible from current (early 1980 designs) with no change in packaging. Among the earliest reviews was a comprehensive 1980 study by DOT whose results were reported in Hsia and Kidd.[1/] The study examined weight reduction for a Chevrolet Impala, Dodge Omni and Ford Fairmont. The first two cars were still in production in 1988 largely unchanged from their design in the late 1970's that was used as the basis for the Hsia and Kidd analysis. This study reported that significant weight reduction was possible in two cases -- an aluminum dominant case and hybrid composite plastic case. The results of the analysis showed that an aluminum dominant design could reduce vehicle weight by 18 to 22 percent while the extensive use of composite structural plastics could reduce weight by 27 to 32 percent.

Table 4-1 shows the change in material use between 1976 and 1988. In 1988, plastics accounted for 7.15 percent of the weight of the car, up only slightly from the 6.4 percent in 1982. Most current plastic applications are for interior components or for front and rear fascias, and very little plastic composite material is used either for outer body panels or structural members.* Until the introduction of the Chevrolet Lumina APV (and its sister Oldsmobile and Pontiac models), plastics in exterior panels was limited to the

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* The now discontinued Pontiac Fiero was the sole exception.

TABLE 4-1

MATERIAL USE IN DOMESTIC
CARS (lbs)

	1976	1980	1984	1988
Carbon steel	2075.0	1737.0	1526.0	1440.0
High strength steel	120.0	175.0	210.0	232.0
Stainless steel	28.0	27.5	28.5	31.0
Other steels	56.0	54.0	54.0	45.0
Iron	562.0	484.0	481.0	459.0
Plastics/Components	162.5	195.0	204.0	223.0
Aluminum	85.5	130.0	136.5	149.0
Glass	87.5	83.5	85.5	85.5
Copper	35.0	35.0	43.5	49.0
Lead	25.0	23.0	24.5	23.0
Zinc castings	44.0	20.0	17.5	19.5
Powdered materials	15.0	17.0	18.5	21.0
Rubber	153.0	131.0	138.0	134.0
Other materials	122.0	73.0	75.5	80.5
Fluids/Lubricants	190.0	178.0	189.0	178.0
Total	3760.5	3363.0	3232.0	3167.0

SOURCE: Metal Working News

Corvette, and a few specialized applications such as fenders for the Buick Reatta and Cadillac, and spoilers for the Camaro and Mustang. The term plastic itself embraces a wide variety of materials and, therefore, can mean different materials in different applications.

While the technology of plastics is still in evolution, there is considerable interplastic competition for specific parts. The current market is dominated by sheet molding compound (SMC), polyurea, and nylon/polyphenylene ether. SMC is used for horizontal panels and polyurea RIM (reaction injection molding) for vertical panels. Typical weight reduction cited for the components are as follows:

• SMC hood and deck lid	20 to 30 percent compared to steel
• Fenders from RIM processed polymers	40 to 50 percent compared to steel
• Polyethylene gas tanks	25 to 30 percent lighter than steel
• Composite Wheels	25 to 30 percent over steel 10 to 15 percent over cast aluminum

Plastics for structural stress bearing parts have not yet been placed in production, but a detailed analysis of such structural plastics is being conducted by a joint industry effort. Current SRIM (Structural Reaction Injection Molded) parts do not have the required surface finish due to the high content of glass fibers. The Corvette has an all plastic bumper in 1989 where the structural beam is also of plastic composite material. In this application, GM has shown an 18 percent weight reduction, combined with a material and labor cost reduction of 14 percent.[2/] A custom molder (Detroit Plastics Molding) has created a radical all plastic bumper, using a thermoplastic fascia, with a structural plastic backing member and energy absorbing foam. Weight reduction of over 30 percent is claimed. Ford is working on an composite structure for its Ford Taurus, and the Ford project manager Dr. Beardmore[3/] has stated that a structural weight saving of about 30 percent was possible.

All of the above weight reduction efforts refer to fiberglass reinforced plastics (FRP). The more exotic graphite fiber reinforced plastics (GRP) has very high weight saving potential of up to 50 percent for structural parts. However, the technology of GRP for mass production may not be ready by 2010 and its costs may continue to be very high. It should be noted that the potential for such large weight reduction exists, and may be possible by 2010.

Under the hood parts have been largely confined to metals, but even here, plastics are making inroads. Among the uses that will occur in the next few years are:

- Engine valve covers (nylon molding)
- Throttle body (phenolic compound)
- Intake manifold (Thermoset polyester resin)

The components above do not amount to a large absolute weight saving (only about 10 lbs total) but are 25 to 35 percent lighter than cast iron/stamped steel parts. An all plastic engine block has been demonstrated, and the entire all plastic engine from Polimoter weights nearly 40 percent less than an equivalent cast iron block/aluminum cylinder head engine. The cost effectiveness and the durability of an all plastic motor is not yet well understood but the technology is possible for 2010.

The weight savings possibility of aluminum is also of great importance. Currently, aluminum is used primarily in radiators and for pistons, while a few sporty models offer cast aluminum alloy wheels as an option. The use of aluminum for the engine is still largely limited to cylinder heads and only about 35 percent of all domestic engine featured aluminum heads in 1988. The only domestic engine using an aluminum block in 1988 was the Cadillac 4.5 liter engine; oddly, this engine uses cast iron heads. The Cadillac engine weighs 18 percent less[4/] than an equivalent cast-iron block engine; with aluminum heads, the engine weight reduction over a cast iron engine will be 22 to 25 percent. (This is based on a fully "dressed" engine with all accessories). In addition, the use of plastic intake manifolds, valve covers and the oil pan, along with the reciprocating part weight reduction can reduce total

engine weight by 25 percent. Weight reduction for reciprocating parts also results in friction reduction and is discussed in that context in Section 4.5

Finally, the packaging efficiency, or the efficiency of design, is also of importance. For a giving level of interior room, it is possible to design a car structure very efficiently. One measure of packaging efficiency is the weight per cubic foot of interior room, not considering trunk volume. Table 4-2 shows this measure for a variety of "notchback" sedans, where the interio room is based on the reported value in the Gas Mileage Guide, and the weight is for a car equipped with automatic transmission and air conditioning.* In general, most front-wheel drive vehicles attain an efficiency of 30 lb/cu. ft or less while older rear wheel drive vehicles are at 35 lb/cu. ft. In general, the larger sizes have lower packaging efficiency because of large front and rear overhang, and also because larger cars have more options such as power windows, power seats and sound insulation. Sports and luxury cars have the lowest packaging efficiency, since they offer other attributes rathe than space as their primary sales pitch.

The range of values illustrated in Table 4-2 by market class shows considerable in-class variation, suggesting significant potential for reducing the average weight per cubic foot simply if the best of today's cars are emulated by their competitors. Unfortunately, current trends are actually going the other way, with cars becoming heavier and more powerful. Under a maximum technology scenario, it can be hypothesized that the cars could be redesigned by 2010 to maximize efficiency.

Clearly, the packaging efficiency based improvements will vary by market class. In minicompact and subcompact cars, the potential to increase efficiency is thought to be small, 3 to 4 percent. Packaging for the large and

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* The table also includes any effects arising from material substitution but most cars do not differ significantly from the average material content level in 1989.

TABLE 4-2

PACKAGING EFFICIENCY OF 1989 CARS (lb/cu. ft.)

Market Class	Best	Worst
Minicompact	23.5	28.1
Subcompact	23.2	30.5
Sports	32.5	40.0
Compact	27.0	31.5
Intermediate	26.0	35.4*
Large	29.5	34.5
Luxury	30.5**	37.8

* Some Japanese intermediate are sold as "near luxury" cars, and have packaging efficiency ratings more in line with the luxury class.

** Front-wheel drive Cadillac with aluminum engine.

luxury cars could lead to a 12-15 percent improvement in efficiency (i.e. a decrease in lb/cu. ft.). A fleetwide average packaging efficiency benefit of 6 to 10 percent is clearly possible. Manufacturers have displayed prototypes of "space maximizing designs". Nissan has unveiled the Boga, an urban car whose interior dimensions make it very nearly an intermediate, but its exterior is the same size as a typical subcompact. The car is marked by very little front and rear overhang, and the shape is unusual.

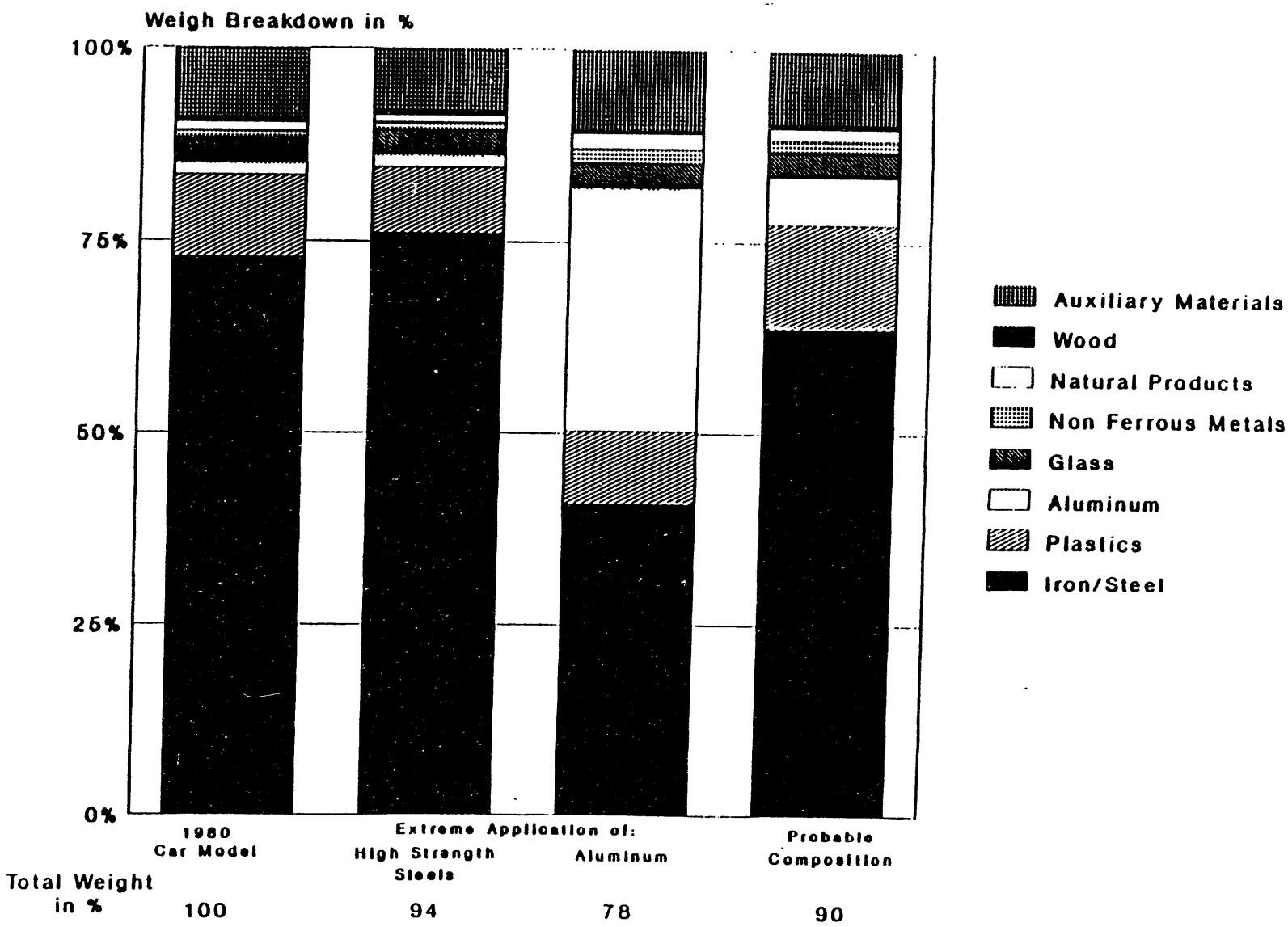
As noted, some components like the seats or the door padding cannot be reduced in weight, but for a typical car with unit body construction the weight breakdown of major components is as follows:

Body Structure	42 - 47%
Engine (dressed)	12 - 16%
Tires and Wheels	7 - 8%
Bumper	3%
Drive Train (RWD)	5 - 6%

While the weight of the propeller shaft, rear differential and drive axle can be largely eliminated with front-wheel drive designs, other components where weight can be reduced 25 to 40 percent account for 65 to 75 percent of the total weight of the car. This suggests a weight reduction potential of 18 to 30 percent from material substitution alone is possible, while another 3 to 10 percent (depending on car size) is available from packaging efficiency. These overall estimates are in good agreement with the 1980 DOT study. In addition, Honda provided data showing an upper limit for their cars of 25% weight reduction, largely from material substitution. VW research[5/] also confirms the weight reduction available from an aluminum intensive car design, as shown in Figure 4-1.

FIGURE 4-1

Material Mix For Various Vehicle Projections



SOURCE: Volkswagen

4.3 AERODYNAMIC DRAG

Aerodynamic drag force is dependent on both the co-efficient of drag, C_D, and frontal area. Aerodynamic drag reduction can be better estimated than total weight reduction because both C_D and frontal area data are tabulated for many cars, and there has been considerable literature in the trade press and engineering journals on low drag shapes.

Ford, an industry leader in aerodynamic research, has unveiled a series of prototypes cars called Probe I, II, III, that have demonstrated progressively lower drag coefficients. The latest has a published C_D of 0.14, but such a vehicle may not be practical in terms of production and consumer acceptance. A practical small car, the Renault VESTA2 demonstrated a C_D of 0.19 and a frontal area of $1.55m^2$. In comparison, the best cars today have displayed a C_D of 0.3 with a frontal area of 1.8 to 2.1 m^2. Of course, the frontal area is related to cars' size, or more accurately, the width and height of the car. One production model, introduced in Europe in 1990 (the opel Calibra), claims a C_D of 0.26.

Japanese automanufacturers and European automanufacturers have shown several advanced prototypes with a C_D of 0.24 to 0.26.[6/] These include the following:

- Intermediate - Nissan NEO-X (C_D = 0.26)
- Subcompact - Citroen Activa (C_D = 0.25)
- Sports - Toyota SERA (C_D = 0.24)
- Sub/minicompact - Toyota AXV (C_D = 0.26)
- Compact - Toyota EXV (C_D = 0.24)
- Compact - Nissan UV-X (C_D = 0.25)

Toyota and Nissan stated that a practical average C_D for 2010 may not be lower than 0.24, while Honda optimistically projected 0.20. Frontal area reductions may range from zero for small cars to 5 percent for larger cars, although this may impact customer comfort related attributes. EEA projects that C_D of

0.23-0.24 will be attainable by 2010, while a minimum C_D of 0.19 or 0.20 may be feasible. Optimistic estimates for frontal area reductions range from zero for subcompacts to 5 percent for large cars, although the most likely scenario suggests that it will remain unchanged.

4.4 DRIVELINE AND TIRE LOSSES

Energy lost in the transmission, axle gears, wheels and tires can be reduced to provide fuel economy benefits. The torque converter in an automatic transmission with full lock-up provides efficiency nearly comparable to a manual transmission and further gains may be unlikely or very difficult to attain. Toyota has recently shown a high efficiency torque converter design but most of these improvements will likely occur by 2000.

Brake drag still exerts a significant force on the wheels. A typical production disk brake exerts a rolling resistance of 16 to 24 in-lb.[7/] This can be almost completely eliminated with drum brakes although drum brakes have problems related to heat dissipation and fade under heavy braking. It is possible that new designs may solve the brake drag problem for disc brakes without need for a new drum brake design. Zero brake drag can cut rolling resistance losses by 5 percent.

Tire rolling resistance has been increasing lately with the greater use of wider (low aspect ratio*) tires better suited for handling and performance. In the 2000-2010 time frame improved polyester compounds, better tread design and tire weight reduction can lead to lower rolling resistance. One possibility is the plastic injection molded tire. Such a tire would largely eliminate the internal belted construction of today's tires that account for the energy dissipation in the rolling mode.

Current tires have rolling resistance co-efficient[8/] in the range of 0.008 to 0.012 with an average of about 0.0090. Detailed data on C_R (rolling resis-

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* Low Aspect Ratio by itself does not increase rolling resistance.

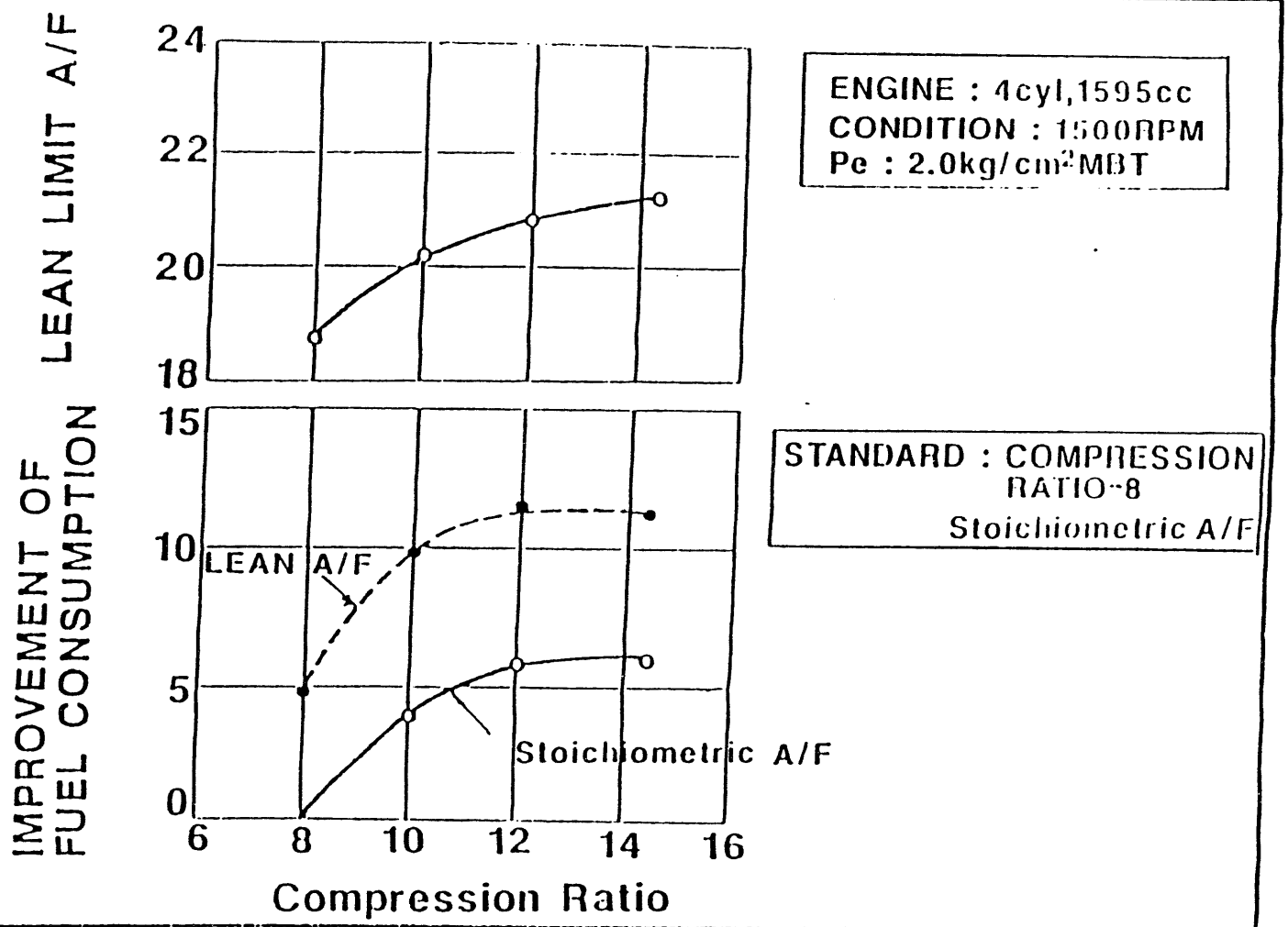
tance coefficient) is not widely available, and the coefficients are largely derived from limited data on tire tests conducted by the EPA. Based on communication from Dunlop, it appears that a rolling resistance reduction to an average of 0.0075 is possible without significant loss in traction and handling from the 1988 baseline. (Of course, current trends may cause rolling resistance to increase). All plastic tires may have rolling resistance as low as 0.006, although the durability and handling properties are not yet well understood.

4.5 CONVENTIONAL ENGINE TECHNOLOGY

The current automobile engine is in a high state of maturity, and further improvements will be largely evolutionary. The components of engine efficiency are thermodynamic efficiency, reduction in pumping loss and reduction of engine mechanical friction.

The thermodynamic efficiency of the engine can be improved by changing the shape of the combustion chamber and increasing the compression ratio. "Fast-burn" heads have been largely incorporated into most of the 1988 fleet. The more compact combustion chamber geometry possible in a four valve engine, along with central spark plug location allows some improvement in compression ratio, CR, from the 9.0 level prevalent in 1988 to a 10.0 level by 2001. Data supplied by Nissan compared the effect of increasing compression ratio from 8.0 to 14.0 at stoichiometric A/F ratio. Increasing CR from 9 to 10 will improve fuel economy by 2 percent, as shown in Figure 4-2. A practical limit of CR is around 11.0, and all Japanese manufacturers suggested that this would occur by 2010, for a net fuel economy benefit of 3.0 percent over the 1988 baseline. Increasing thermal efficiency is also possible with variable compression ratio. Volkswagen modified a Golf GTI car engine with a variable compression device, allowing CR to be varied between 9.0 to 15.0.[9/] Such a system was found to increase fuel economy on the ECE test cycle by 14.5% (decreasing fuel consumption by 12.7%), and 90 km/hr constant speed fuel economy by nearly 17 percent. However, the ability of such a concept to meet future emission standards is not yet well understood.

FIGURE 4-2



NISSAN

EFFECTS OF HIGH COMPRESSION RATIO

Lean operation which improves thermodynamic efficiency and decreases pumping loss results in a five to six percent improvement in fuel economy, as shown in Figure 4-2. For a lean-burn engine operating at 11.0 CR, this implies a total benefit of 9 percent in fuel economy relative to the current 9.0 CR baseline and stoichiometric operation. It is difficult to decompose this into pumping loss reduction and improved thermodynamic efficiency, but an estimate is that pumping loss is reduced by twenty percent, while thermodynamic efficiency increases four percent.

Other methods to decrease pumping loss involve use of multi-speed transmissions that allow the engine to operate at a slower speed and a higher local. Many vehicles in the 1988 baseline utilize 4-speed automatic transmissions. The use of 5-speed automatic and 6-speed manual transmissions will occur by 2000-2005 largely to take advantage of the lower power requirement at highway speeds from drag reduction. The synergistic effects of multi speed transmissions and drag reduction are difficult to translate into the components of reduced pumping loss, reduced engine friction as well as the more obvious drag reduction. At highway speeds, friction reduction could be proportional to the reduction of engine RPM of (typically) 10 to 20%. Since the load on the engine is increased proportionately, pumping loss at highway speed will be reduced, and the magnitude of the reduction is about 10 percent.

Intake valve control reduces pumping work primarily at low loads by changing the valve timing. This technology is expected to be widely used by 2000 and its characteristics have been extensively documented in other reports, and are not repeated here.

Friction reduction will occur from the use of such items as roller cam followers, reduced piston ring tension, improved manufacturing tolerances and the use of 5W-30 oil or synthetic lubricants. In addition, friction and energy use in the valve train will be reduced by decreasing the weights of various reciprocating components. At the meeting with EEA, Toyota provided detailed estimates of part by part weight reduction as shown below:

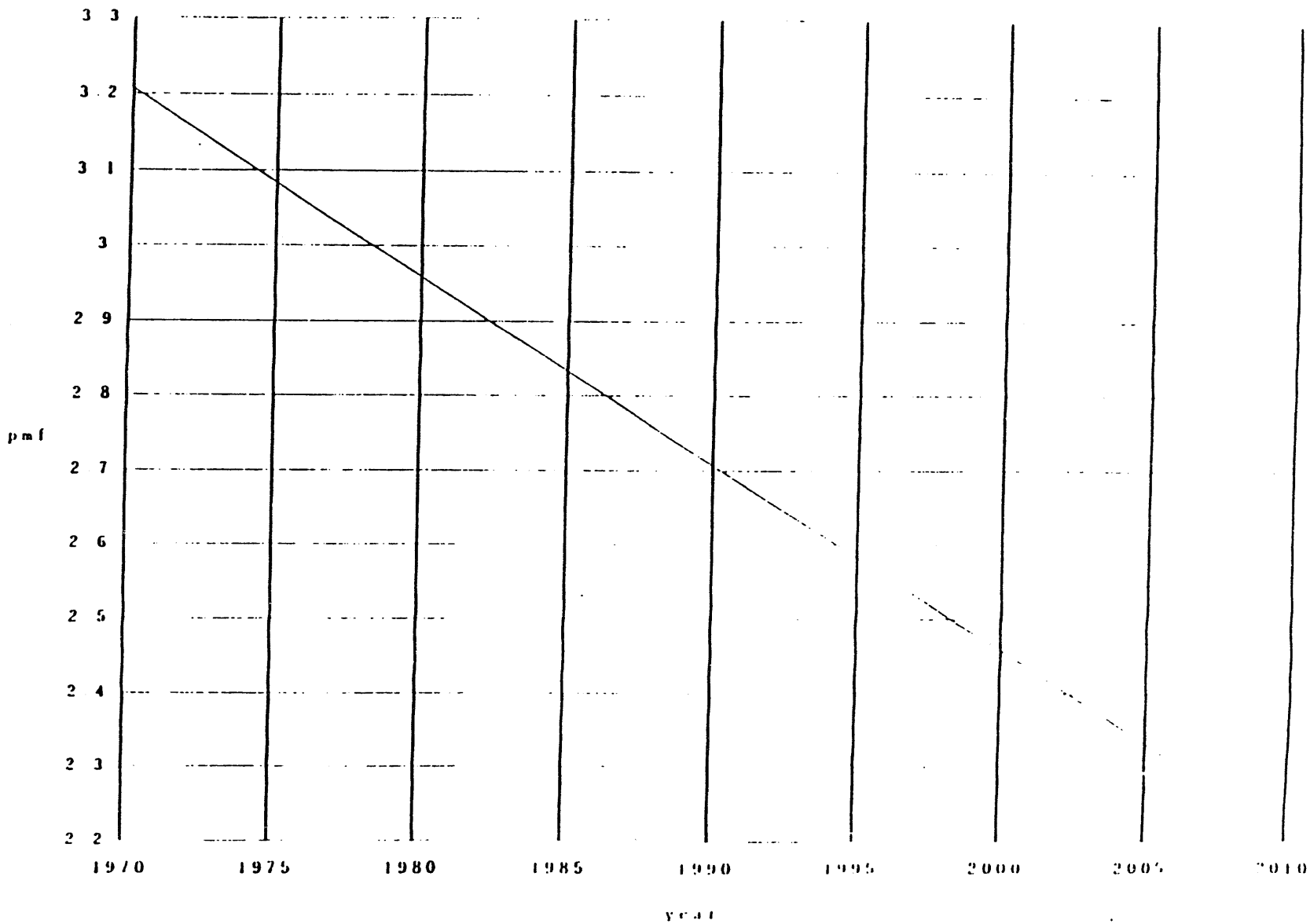
• Titanium valves	-	40 percent lighter than steel valves
• Ceramic valves valves	-	60 percent lighter than steel
• Titanium alloy valve springs	-	60 percent lighter than steel, with a 20 percent height reduction
• Plastic/metal camshaft	-	20 to 30 percent lighter than steel camshaft
• Composite (metal matrix) connecting rod	-	30 percent lighter than steel
• Aluminum Lifters	-	40% lighter than steel
• Ceramic shims	-	60% lighter than steel, higher wear resistance
• Composite Fiber Reinforced Magnesium Piston	-	25% lighter than aluminum piston
• Two ring piston	-	Eliminates second compression ring.

As can be seen, most reciprocating parts can be reduced in weight by 25 to 60 percent. The net contribution to reduced friction and wasted energy is not large, but the weight reduction also lower shaking forces, making the use of the four cylinder engine more attractive from the consumer acceptance point of view. Honda provided data showing that internal friction is reduced by about 10 percent per decade, as in Figure 4-3. This estimate does not include the effect of pumping loss as part of the total frictional load. In addition, friction reduction from reducing the displacement or running the engine slower is not included.

It is also possible to increase engine specific output further, both by the inclusion of variable valve timing and by using five-valve per cylinder technology as opposed to the conventional 4-valve technology. Five valves per cylinder provides a gain of 20 to 25 percent in total airflow area and output levels of 80 to 100 HP/liter are achievable for 5-valve/variable valve timing combination.[10/] However, the system is both complex and may not have enough low end torque for common applications. The offsetting advantages of the

FIGURE 4-3

REDUCTION IN FRICTION MEAN EFFECTIVE PRESSURE



SOURCE: Honda

five-valve design are that it provides greater flexibility in selecting spark plug diameter. Bore diameter can be reduced 10 percent if the same valve area is desired, with a correspondingly compact combustion chamber. The five-valve engine investigated by Yamaha provides a 10 percent improvement in high speed volumetric efficiency over a 4-valve design. The mass of each valve dropped by 12 percent, reducing valve train loss, and increasing redline RPM. Such a system could be utilized in sports and luxury cars.

One technology that was utilized briefly by GM (in 1982) but dropped after a year, is modulated displacement. This technology results in closing off valves of some cylinders under part load condition. This idea has been tried in numerous forms, starting with fuel cutoff to the cylinders and ranging up to the variable displacement type engine. The valve shutoff method reduces both pumping work and friction losses in the valve train. Mitsubishi has recently unveiled a modulated displacement engine in Japan[11/] and provided data on fuel economy benefits for range of intermediate concepts as follows.

- Fuel shutoff - 26% at idle, 8% at 60 km/hr
- Fuel shutoff and EGR - 37% at idle, 8% at 60 km/hr
- Fuel shutoff and unthrottled air - 37% at idle, 8% at 60 km/hr
- Valve deactivation - 42% at idle, 16% at 60 km/hr

The percentage improvements are based on shutoff of 2 cylinders of 4. All of the fuel shutoff/valve deactivation concepts do not have favorable synergy with other concepts discussed such as lean burn, or intake valve control. Hence, the modulated displacement engine benefits can be largely duplicated by other methods which may be simpler to implement or produce better driveability.

In summary, the following improvements are possible for conventional spark ignition engines starting from the 2000 baseline of a 4-valve engine with valve lift and timing control.

• 5-valve engine	-	increased specific output reduced pumping loss
• CR increased to 11.0	-	improved thermal efficiency
• Variable CR	-	optimized thermal efficiency
• Lean Burn	-	Reduced pumping loss small increase in thermal efficiency
• Two ring piston	-	reduced ring friction
• Lightweight ceramic or composite material reciprocating parts	-	reduced friction reduced valve gear energy loss

Of the above, variable CR and lean burn can be considered as the most difficult to achieve. A more detailed characterization of engine improvements is provided in Table 4-3, which provides estimate of pumping loss and friction loss reductions.

4.6 ALTERNATIVE ENGINES

Although a wide variety of engine types have been researched, the current consensus is that there are only three viable alternatives to the current conventional gasoline engine. These are the:

- Direct injection stratified charge engine (4-stroke)
- Two-stroke engine
- Diesel engine

The direct injection stratified charge engine has been heavily researched, and almost went into production in the early 1980's as Ford's PROCO engine. Its principle advantage lies in its ability to run at very lean air-fuel ratios, thereby enhancing thermal efficiency and decreasing pumping loss. However, the conventional engine with variable valve timing, more modest lean burn and possibly, variable compression ratio, can provide a large fraction of the

TABLE 4-3

SUMMARY OF ENGINE IMPROVEMENTS

Thermal Efficiency Improvement		% Change in η_T
1988-2001	Increase CR to 10 (4 valve)	+2.0
2001-2010	Increase CR from 10 to 11	+1.2
	Variable CR from 11 CR	+2.0
	Lean Burn	+1.5
	Total[1/]	5.29/6.87
Pumping Loss Reduction		**% Change in P**
1988-2001	4-valve engine	-10.0
	Intake valve control*	-30.0
	5-speed automatic*	-7.0
2001-2010	5-valve engine	-10.0
	Lean Burn*	-25.0
	Modulated displacement*	-30.0
	Total[2/]	45/66
Friction Loss Reduction		**% Change in F_r**
1988-2001	Roller cams	-10 to -15
	Low Tension Rings	-10.0
	Low Mass Advanced Piston	-2.5
	4-valve valve wt.	+2.5
	Improved manufacturing/design	-5.0
	5-speed automatic	-5.0
2001-2010	Ceramic valves/titanium spring	-2.5
	Two Ring Piston	-5.0
	5-valve engine	-2.5
	FRM Piston/con rod	-2.5
	Total	36-39.3

TABLE 4-3

SUMMARY OF ENGINE IMPROVEMENTS
(Continued)

Assumed Baseline for Improvements

Base Engine: 2-valve OHC engine, 9.0 CR, 50 BHP/l

Transmission: 4-speed auto transmission

Vehicle: WT/HP Ratio = 23 lb/hp

Pumping loss fraction = 0.18

Friction loss fraction = 0.21

1/ With and without lean burn.

2/ With and without lean burn/modulated displacement.

3/ Not combinable directly with other technologies marked with asterisk.

benefits associated with direct injection stratified charge in a more simple and less costly way. As a result, the 4-stroke direct injection stratified charge engine appears unlikely to provide significant additional fuel economy benefits, although its costs are high.

The advanced two-stroke engine has been in the news lately, and differs from the conventional two-stroke in having direct injection of fuel, in addition to forced scavenging. The combustion process is similar to the direct injection stratified charge four-stroke engine. The two-stroke, by virtue of having one power stroke for each revolution, has a significantly higher level of power output per unit to displacement, in the range of 80 to 100 HP per liter. In addition, the higher frequency of power strokes reduces torque fluctuations considerably, by a factor of 50 percent. The engine produces high torque at low speeds, in contrast to 4-stroke engines with 5 valves per cylinder where the increase in horsepower at high RPM is not matched by the torque increase at low RPM. The inherent smoothness allows a three cylinder 2-stroke engine to replace a six-cylinder 4-stroke engine with virtually no change in NVH (noise, vibration, harshness).

The lower weight and reduced friction of the smaller three-cylinder engine is further augmented by the absence of a valve train in some designs. Toyota's 2-stroke utilizes a four-valve design that does not have the friction advantage of a port-type design. Offsetting these advantages however, are:

- The reduced thermal efficiency of the two-stroke cycle
- The need for a supercharger/blower for forced scavenging
- The need for a high pressure fuel injection pump with additional air for atomization
- A potential increase in piston friction associated with need for a large piston skirt.

Over and above the mechanical questions are the questions about the ability of the engine to comply with emission regulations. Due to forced air scavenging, the exhaust stream is lean, and three-way catalysts to reduce NO_x is not yet

an applicable emission control technology. This problem may be solved with better control of airflow and it appears possible that the engine can meet future NO_x standards with further development.

The benefits of the engine in terms of fuel economy are difficult to predict. First, the engine power output and low end torque suggest that a smaller engine with fewer number of cylinders (with reduced friction) can be used to replace a conventional four-stroke engine. Second, the direct injection system can be used for lean burn. These factors could be offset by the supercharger drive energy and the reduced thermal efficiency due to incomplete gas expansion. The range of possible fuel economy benefits are as follows, in comparison to a 4-valve/4-stroke engine:

Effect of weight reduction	+2 to +4
Effect of friction reduction	+3 to +5
Direct injection/lean burn	+6 to +9
Decreased thermodynamic efficiency	-2 to -4
Scavenging air flow energy	-2 to -4
Net Benefit	7 to 10 percent

The net benefit estimate is in accord with the limited published data. Thus, the benefits are comparable to a 5-valve engine with variable valve timing at the conservative end of the benefit range, or 5-valve direct-injection lean burn engine at the optimistic end. However, it must be noted that the two-stroke engine could provide these benefits at a lower cost, if technical problems are overcome.

Diesel engines are the proven technology for large fuel economy benefits, although with attendant drawbacks on weight, specific output, and emissions. Nevertheless, it is interesting to compare the performance of diesels relative to gasoline engines of "equal" performance. It is difficult to obtain an exact comparison since the diesel engine has better low RPM torque characteristics and poorer high RPM torque characteristics relative to gasoline engines. Table 4-4 shows the fuel economy comparison for the only 4 carlines

TABLE 4-4

COMPARISON OF DIESEL/GAS FUEL ECONOMY - 1987 CARS

	Ford Escort		Mercedes 190 2.3/2.5D		Mercedes 260E/300D		Peugeot 505	
	Gas	Diesel	Gas	Diesel	Gas	Diesel	Gas	Diesel
Type	OHC	OHC	OHC	OHC/Turbo	OHC	OHC/Turbo	OHC	OHC/Turbo
Displacement	113	122	140	152	158	183	120	152
Horsepower	84	58	130	123	158	143	97	95
Torque (ft-lb)	105	84	146	162	162	195	116	133
Test Weight	2625	2875	3250	3375	3625	3750	3375	3500
Dyno HP	7.5	6.8	8.2	82.	7.5	7.5	10.3	10.3
Transmission	M5	M5	A4	A4	A4	A4	L4	L4
Axle Ratio	3.52	3.52	3.27	2.65	3.27	2.65	4.11	3.89
City F/E	31.4	40.7	23.0	31.5	21.6	28.7	22.3	27.2
Highway F/E	47.2	57.3	30.7	41.5	29.9	37.9	30.5	35.9
Composite F/E	37.0	46.8	25.9	35.3	24.7	31.8	25.4	30.5
Diesel Benefit (%)	--	26.5	--	36.3	--	28.7	--	20.1

available in 1987 in which the diesel was an option. The comparisons of the two Mercedes cars and the Peugeot 505 are very close to meeting the constant performance criterion, and it can be seen that a turbocharged diesel provides 20 to 30 percent better fuel economy even after accounting for the weight penalty. It can be argued that the larger benefits for Mercedes models are because its gasoline models are not optimized for fuel economy; the Peugeot diesel, however, obtains a 4 percent lower fuel economy than the more powerful and heavier Mercedes diesel and the diesel engine appears to be less efficient than possible. The diesels shown in the table are all of the indirect injection or prechamber type. More recently, the direct injection (DI) diesel has seen limited passenger car application in Europe. The DI diesel, long used in heavy truck applications, was rated by VW and Mercedes as being 12 to 15 percent more efficient than the prechamber diesel. Previously, the engine had problems meeting NO_x standards and particulate emission standards currently in force. These problems have been largely solved; Audi is planning the introduction of a DI diesel in the U.S. for model year 1991.

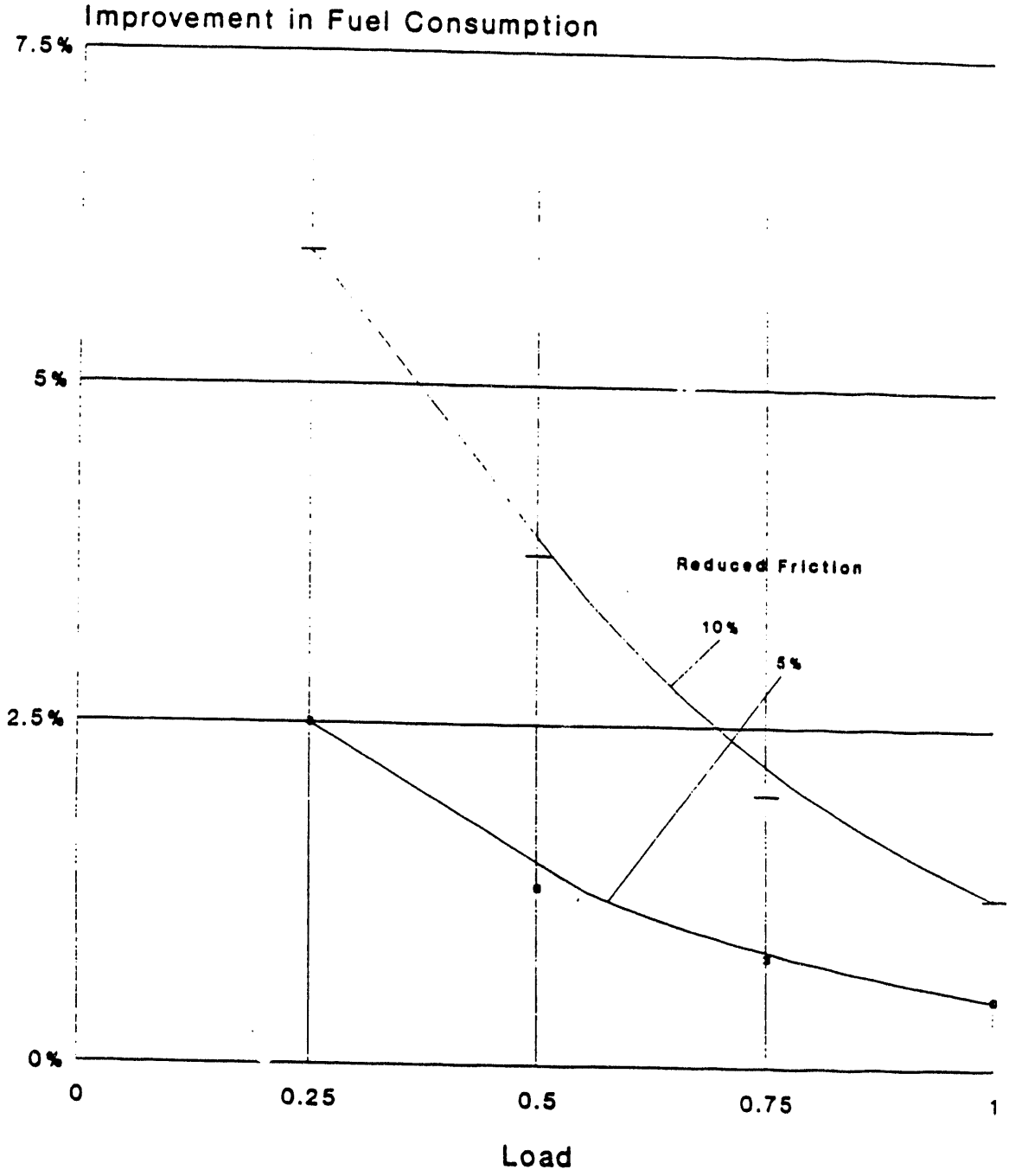
European manufacturers believe that at constant performance, the following benefits are obtained over a gasoline two-valve engine.

- Naturally aspirated - 15-18 percent
- Turbocharged - 24-28 percent
- Direct injection turbocharged - 35-40 percent.

The diesel engine can also be improved with components similar to those used in gasoline engines. Clearly, "lean burn" is already a diesel technology, and little improvement from pumping loss reduction is possible. However, engine friction reduction is much more effective in improving fuel economy. Volkswagen provided data on the internal friction of a diesel engine,[11/] and a 10 percent reduction in engine friction can increase fuel economy by five percent at 1/3 load, as shown in Figure 4-4. This is equivalent to the benefit obtained from a 15 percent reduction in friction <u>and</u> a 15 percent reduction in pumping loss for a gasoline engine. Conceptually, friction reduction for a

FIGURE 4-4

Influence of Reduced Friction on
Fuel Consumption as a Function of
Engine Load



Source: VW

diesel engine can utilize the low mass reciprocating components, improvements in piston and ring design, etc., described for gasoline engines and the friction reduction payoff will be three times as large in a diesel as for a gasoline engine. Of course, the piston and rings are the largest contributor to total diesel engine friction, and reduction in valve train friction may not provide as much economy benefit as reduction in piston/ring friction. Lack of data precluded as detailed an analysis of future diesel engines as was performed for S.I. engines. We have simply assumed that a 2010 turbocharged D.I. diesel with a trap will have 45 percent better fuel economy than a 1988 OHC/2V spark ignited engine.

The ability of a diesel to meet more stringent emission standards is in some doubt. It now appears that particulate traps can reduce particulate emissions to levels below 0.05 g/mile. NO_x standards of 0.4 g/mile may be more difficult to meet. Only VW was optimistic that a diesel could likely meet a 0.4 g/mi NO_x standard, but this may hold true only for small lightweight cars. It may also become possible to use a catalyst to reduce NO_x; there is considerable worldwide activity in "lean" catalysts for NO_x and Japanese researchers have recently expressed optimism on its feasibility. Such a development could allow diesels to meet even the NO_x standards being discussed for the post-2000 time frame.

4.7 ENERGY STORAGE/IDLE SHUTOFF

Idle fuel consumption is largely a function of the engine size and engine RPM at idle. The benefits of friction reduction and idle pumping loss reduction are very high for idle fuel consumption, since the useful power output to drive accessories is relatively low. The rest of the energy is used to overcome engine losses. For example, roller cam followers can show provide a 7 to 9 percent benefit in idle consumption, while intake valve control can reduce idle consumption by 15 to 20 percent. The Mitsubishi valve shutoff device that enables shutoff of half of cylinders provides a 40 percent reduction of idle fuel consumption. The effects of these devices on FTP and idle consumption have been discussed in Section 4.5.

The most efficient form of idle fuel consumption reduction is by shutoff of engine at idle. Approximately 10 percent of all fuel consumed is at idle (16-20 percent for idle and during braking). Volkswagen has pioneered the idle stop/start system which switches the engine off as soon as the car is stationary. Unfortunately this also shuts down all accessories, and so air conditioning is difficult. In winter, the frequent engine shutdown in city driving conditions may result in very poor heating availability. In addition, VW believes that it is difficult to keep the battery charged in winter if the rear window defroster is used; electric interior heating is out of the question.

A second major problem with the stop/start system is the difficulty of instantaneous restart with a gasoline engine. Hot restarts sometimes requires two to four engine revolutions, creating a restart delay that is unacceptable in many driving conditions. For this reason, VW has largely concentrated its stop/start research on cars with diesel engines. Diesel engines restart reliably in half a revolution when warmed up. The original E-80 stop/start VW concept car was a VW Polo (not sold in the U.S.) modified with drag reduction devices, low rolling resistance, tires, and supercharged 3 cylinder direct injection 1.2L diesel rated at 50 HP. Gear ratios were selected to maximize fuel economy. A flywheel based stop/start system was utilized that allowed the flywheel to keep rotating during braking and was decompiled from the engine. The flywheel then provides the energy to restart the engine as soon as the accelerator pedal is depressed. The E-80 concept was rated at 83 MPG (combined), more than double the fuel economy of the spark ignited engine equivalent to a fuel consumption reduction of 57 percent. Of this, only six percent was due to the engine stop/start system.

More recently, VW has developed the Oko-Polo and Oko-Golf concepts that utilize very low emission diesel engines. These utilize electric restart with the conventional starter motor, and are closer to production type cars. In both these vehicles, heating and battery charging in winter are still problematic. As a result, the stop/start system is unlikely to see wide scale commercialization in the U.S.

Another new development is the Diesel/Electric Hybrid shown by Volkswagen. In this type of design, a small (8.0 HP) electric motor is used in conjunction with the diesel engine. Once the engine is warmed up, it is used only above certain speeds/loads or else shutdown completely. The electric motor runs the car at low speeds or low acceleration rates, typical of central city driving. Under city driving conditions, the electric motor is used for speeds up to 30 mph. The vehicle used is the Golf with the 1.6 liter diesel engine. The electric motor functions as the starter and as the generator for charging the battery when the engine is running. The car becomes significantly heavier, and is described in Section 5.

The extra weight of the car and the inefficiencies with the electric system do not make the car efficient in absolute terms. The battery must be charged directly from the city electric supply and not from the diesel engine (except in emergency situations) or else the vehicle energy efficiency suffers considerably. However, the VW diesel/electric concept accomplished three objectives:

- it reduces petroleum consumption if central electric generation is derived from other sources such as coal or nuclear
- it reduces urban emissions
- it may allow the diesel be certified low NO_x standards

The hybrid car obtained about 60 MPG (energy equivalent) in the city compared to only 37.4 MPG for the Golf diesel. Although the diesel/electric car MPG is high compared to the diesel, it should be recognized that the inefficiencies of converting fossil fuel to electricity are <u>not</u> included in the above 60 MPG value.

It is quite possible that the vehicle can be improved even further. It's biggest hurdles are the heavy weight and low capacity of lead acid batteries. Isuzu has recently unveiled an advanced "capacitor battery" that can be recharged in 30 seconds, and weighs significantly less than a lead-acid battery of similar capacity. This factor, combined with the intriguing

possibilities of allowing diesel engines to comply with emission standards (if current test procedures are still allowed for the hybrid) make this vehicle type a strong contender for 2010. The current diesel Golf shows a 50 percent gain in fuel economy on an equivalent energy basis, but this could possibly be increased to 75 to 100 percent. However, for the purposes of this analysis we have assumed that a 60 percent gain in equivalent fuel economy and 100 percent gain in oil-based fuel economy will be possible.

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5. FORECAST OF FUEL ECONOMY FOR 2010 AND COMPARISONS TO ADVANCED PROTOTYPES

5.1 ANALYSIS OVERVIEW

Any projection of fuel economy into the distant future is subject to considerable uncertainty. In making projections to 2010, EEA has assumed that the car market does not change dramatically - i.e., consumers still like attributes such as space, luxury features and options, smooth ride and good acceleration and handling performance. There can, of course, be relative shifts in the demand for such attributes, but the assumption in this analysis is that the range of products available today capture the range of attributes that will be demanded over the next twenty years. The implication of this assumption is that fuel economy can be forecast by market class, and all demand shifts to 2001 can be represented as a different sales mix of classes rather than the emergence of new market classes. As a result, we have not analyzed possibilities such as a one-seat commuter vehicle, or a limited range electric vehicle, or even a very low performance conventional vehicle.

Even with this assumption, it must be recognized that the benefits and costs of post-2000 technologies are subject to more uncertainty than the equivalent parameters for technologies available in the next ten years. Compounding the uncertainty is the possibility of new emission regulations that may be unattainable by future technologies considered in Section 4. Lastly, it is by no means clear that all of the technologies considered will meet the criteria required for manufacturability and customer acceptance. These manufacturing and marketing risks are present at different levels for the different technologies, and it is difficult to provide an objective measure of this factor. The approach chosen in this analysis is to qualify the risks as belonging to three levels, where:

- Level I is the risk level that would correspond to most automotive engineers agreeing that the technology is likely to be commercialized by 2010
- Level II is for technologies where opinion is sharply divided about either the benefits of the technology or its commercial prospects
- Level III is for technologies that are considered esoteric by most, but still within the realm of possibility.

The technology benefits were subject to the above risks but even less is known about costs. In the past, EEA has provided DOE with a "payback period algorithm" which projects benefits as a function of technology cost (or, more accurately, price) by market class. Forecasting costs and benefits at this level of detail becomes impossible in the post-2000 time frame, and a risk based approach is more applicable in this case.

A forecast of average fuel economy for all cars is provided for 2010, assuming that the mix of cars sold in 2000 and the attributes of each market class remains constant to 2010. The estimate relies on the new calculation methodology developed in Section 3 of this report. These estimates are then compared to available data from advanced prototypes.

5.2 RISK-BASED LEVELS OF FUEL ECONOMY FOR 2010

In earlier analysis for the DOE, future fuel economy was based on a specific fuel price path. Cost-effective levels of fuel economy were based on trading off fuel economy technology cost against the discounted value of fuel savings over a specified time period, typically either four years (reflecting a new car buyer's holding period) or ten years (the average lifetime of the car). These approaches are not useful for defining the maximum potential fuel economy for 2010 not only due to uncertainty about fuel prices and technology costs, but also due to the fact that the DOE is addressing the issue from other policy perspectives such as energy security.

The steps utilized to provide an assessment of 2010 risk-based maximum fuel economy are

- recalculation of the 2001 baseline
- definition of technologies in each risk class
- derivation of 2010 fuel economy levels.

The 2001 forecast discussed in Section 2 was recomputed using the analytical methods outlined in Section 3, and using the engine specific details for friction reduction and pumping loss reduction from the data provided in Section 4. Since detailed data were available starting only from an overhead cam, 2-valve engine baseline, the recomputation was based on an "adjusted" baseline.

The "adjustments" were made to the 1988/89 baseline to account for the fact that engine improvements where specified over a 2-valve per cylinder overhead cam (OHC) engine baseline and to account for future emission and safety standards. The adjustments also accounted for front-wheel drive conversion in all classes of cars except sports cars. The nature of the adjustments were as follows. First, the average characteristics of the 1988 fleet by market class was determined. Second, the average class characteristic was adjusted for front-wheel drive (FWD) penetration in all classes except "sports" so that the baseline reflected 100 percent FWD. Third, for each class a representative car was chosen if its characteristics of weight, horsepower and fuel economy were nearly identical to the computed average. Fourth, its fuel economy was decreased by 3 percent and weight increased to account for safety/emission standards to 2001. Lastly, if the selected car did not have a 2-valve OHC engine, its fuel economy was adjusted by the factor defined in Section 2 for the 2-valve OHC engine.

An example illustrates the baseline adjustment process. The actual baseline for large cars in 1988 was as follows:

Curb Weight	-	3475 lb
Engine Displacement	-	256 cu. in
Horsepower	-	155 HP
Composite Fuel Economy	-	24.8 MPG
Front Wheel Drive	-	59%

Conversion of the 41% of rear wheel drive vehicles to front wheel drive would decrease weight to 3300 lb and increase fuel economy to 25.8 MPG i.e. 24.8 (1 + 0.41 x 0.1). Examination of the 1989 data revealed the Buick LeSabre to have exactly the predicted characteristics at 3296 lb and 25.8 MPG. The engine is a 3.8 L "advanced" OHV rated at 150 HP. In order to convert it to an OHC engine, the engine displacement is reduced 10 percent to 3.4L, which provides a rating of 170 HP at 50 HP/L. The 3 percent benefit in fuel economy due to the OHC engine is exactly <u>offset</u> by the 3 percent decrease due to safety and fuel economy standards. Weight is increased by 100 lb due to the air bag and side impact requirements. The same process was applied to other classes and the resultant adjusted baseline is shown in Table 5-1.

The adjusted baseline also explicitly states the inclusion or exclusion of low friction rings and roller cam followers which are individually accounted for in the summary table on engine improvements in Section 4. Starting from the adjusted baseline, fuel economy was derived from two equations, one relating to the improvements in engine bscfc over the composite cycle and the second to the reduction in energy required to move the car over the cycle. They are

$$\frac{bsfc}{bsfc_o} = \frac{\eta_{To}}{\eta_T} \frac{(1 - P - Fr)_o}{(1 - P - Fr)}$$

$$\frac{dE}{E_o} = \left[0.54 \frac{dM}{M_o} + 0.23 \frac{dC_D}{C_{Do}} + 0.25 \frac{dC_R}{C_{Ro}} + 0.1 \frac{dE_A}{E_{Ao}}\right]$$

and $$\frac{FC}{FC_o} = 0.90 \frac{bsfc}{bsfc_o} \left(1 - \frac{dE}{E_o}\right) + 0.1 \frac{G_I}{G_O}$$

TABLE 5-1

CHARACTERISTICS OF BASELINE CARS USED FOR 2010 FORECAST

	Luxury	Large	Midsize	Compact	Sports	Subcompact	Minicompact
Curb Weight	3650	3400	2930	2655	2925	2360	1765
Drag, C_D	0.42	0.38	0.33	0.34	0.34	0.37	0.35
Engine CID	240*	225*	165*	133*	181	113	81
HP	175*	170	140	110	150*	90	58
Transmission	L4	L4	L4	L4	L4/M5	L4**/M/5	M5
F/E (Adjusted)	23.9	25.8	27.6	29.9	25.5	34.0	44.4
Example Model	(1989) Buick Electra	Buick LeSabre	Ford Taurus	Honda Accord	Dodge Daytona	Ford Escort	Kia Festiva
Roller Cam Followers	Yes	Yes	No	No	No	Yes	No
Low Friction Piston/ Rings	Yes	Yes	Yes	No	No	Yes	No

* Equivalent performance OHC/2V naturally aspirated engine displacement.
** Adjusted from L3 transmission.

where the zero subscript refers to the baseline. As noted, we have assumed conservatively that idle fuel consumption decreases will parallel bsfc decreases and G_I/G_{IO} will be equal to $bsfc/bsfc_o$.

The above method provides the correct mixture of additive and multiplicative factors in the calculation. The baseline values for P and F_r were set 0.18 and 0.21 respectively, and reduction of these variables was calculated directly from the data in Section 4. It was noted that only 80 percent of the reductions in P and 67 percent of the reduction in F_r could be translated into reduction in fuel consumption, and these factors were also utilized. The net calculation showed the 2001 estimated fuel economy was 37.53 MPG for domestic cars, which is 2 percent higher than the 36.8 MPG forecast in Section 2 using the linearized method. Of course, the higher result was anticipated since this method more correctly accounts for some favorable synergies. It should also be noted that the coefficients chosen for the equation are quite conservative; the theoretical coefficients indicate even greater potential for improvement.

As noted, the risk class based definitions were based on subjective responses of the engineers at the auto manufacturers interviewed. Risk Level I technologies are as follows:

Weight Reduction	- Extensive use of aluminum and fiberglass reinforced plastics in standard parts.
Drag Reduction	- Fleetwide average C_D levels of 0.24 with no reduction in frontal area.
Improved Packaging	- An increase of packaging efficiency by 4 percent for large and luxury cars and by zero for minicompacts. Other size classes are intermediate to these levels.
Improved Tires	- Rolling resistance of tires will decline to a C_R of 0.0075 from the 2001 value of 0.0085

Engine Improvements - All engine improvements listed in Section 4 except lean-burn or modulated displacement are utilized.

Under risk Level II, it is assumed that modulated displacement engines or lean burn or the direct injection stratified charge two stroke engine will become available in the 2000-2010 time frame. In addition, the maximum weight reduction, drag reduction and packaging efficiency benefits available for vehicles are fully exploited. The technology changes to Level II are as follows:

- Weight reduction - All vehicles are estimated to be reduced in weight by 15 percent from 2001 due to the use of graphite reinforced plastics and extensive use of aluminum.
- Drag reduction - An average C_D of 0.20 is anticipated for vehicles undergoing drag reduction, coupled with frontal area reduction ranging from 5 percent in large cars to zero in minicompacts.
- Improved packaging - A weight reduction of 8 percent is forecast only for large luxury cars with a 3 percent reduction for minicompacts; weight reduction for other size classes lie between these values.
- Alternative engines - The diesel engine with direct injection and turbocharging is assumed to enter the market in specific segments.

The introduction of diesel engines is predicated on the retention of the 0.4 g/mi NO_x standard and is restricted to cars in the minicompact, subcompact and compact classes. The assumption here is that diesels can meet a 0.4 g/mi NO_x level on cars where weight is below 1000 kg (2200 lb) and that its penetration will be 20 percent in such vehicles. Table 5-2 summarizes the assumptions on all technologies at Risks Levels I and II.

Under Level III risk we have included the following technologies:

- The development of a "lean-catalyst" to enable DI diesels to be used in any vehicle size regardless of low NO_x standards

TABLE 5-2
2010 ASSUMPTIONS ON TECHNOLOGIES
AT DIFFERENT RISK LEVELS
(Relative to Baseline)

	Risk Level I	Risk Level II
Weight Reduction	18% weight reduction on all cars	25% weight reduction on all cars
Drag Reduction	C_D = 0.24 for all cars	C_D = 0.20 for all cars
Frontal Area Reduction	0	0 for minicompact to 5 for large/luxury
Improved Packaging	0 for minicompact to 5 for large/luxury	3 for minicompact to 8 for large/luxury
Engine Friction Reduction	As per Table 4-3	As per Table 4-3
Pumping Loss Reduction	45%	66%
Thermal Efficiency Improvement	5.3%	6.87%
Rolling Resistance Reduction	15%	25%
Diesel Engine Market Penetration	0	20% of mini, sub, and compact classes

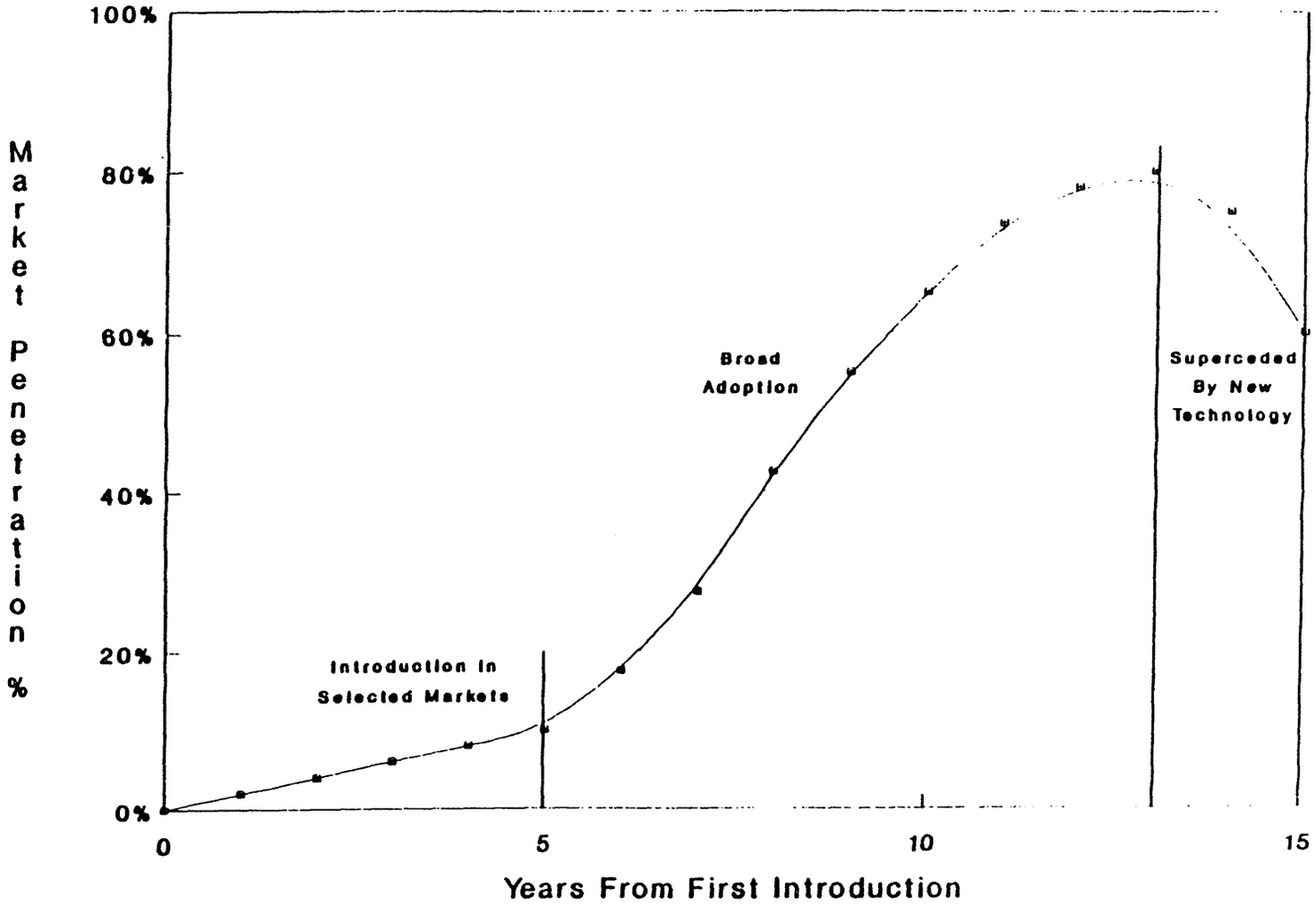
- The use of energy storage mechanisms that can be either of the electric or flywheel types, in conjunction with a IDI diesel engine.

It is possible that the energy storage mechanism itself would permit DI diesels to meet low NO_x standards.

A key aspect of the calculation of fuel economy at any level of risk is the technology market penetration achieved. Historical experience suggests that most new technologies are introduced into the market place in specific niche market vehicles initially so that manufacturers can gain experience with the technology and assess consumer reaction to the technology. Typically, this phase lasts about 5 years, and market penetration levels of 5 to 10 percent are achieved. Assuming the technology has no major negative attributes, a second phase of broad adoption in the market place occurs as the technology is utilized in mass market vehicles. This phase can occur quickly, but a typical period of eight years is common, reflecting the length over which most manufacturers redesign their entire product line-up. This period can last 12 to 16 years for engine technology. A maximum market penetration of 80 to 85 percent of applicable vehicles is a reasonable peak (applicable refers to the fact that certain improvements are useful only for certain cars, e.g., torque converter lock-up for cars with automatic transmissions). The decline phase is associated with newer technologies that replace a particular technology. For example, four-valve engines will replace two-valve engines, and five-valve engines will eventually replace four-valve engines. The 80 to 85 percent maximum penetration is due to the fact that some cars designed for low cost may never utilize the new technology, while others may bypass the technology and move directly to even newer technology. For example, GM has a four-valve OHC engine replacing a two-valve OHV engine, skipping over the intermediate development stage of a two-valve OHC engine. The market penetration profile is shown in Figure 5-1.

Figure 5-1

Typical Market Penetration Profile of New Technology



Fuel economy calculations for the year 2010 are based on the entire fleet and not just "domestic" cars. In 20 years, the status of industry and "domestic" and "import" designations may have shifted radically and are essentially unimportant to DOE concerns. As a result, the fuel economy computations were performed for all market classes and aggregated based on fleet wide 2001 sales mix. The actual 2010 mix will be dependent on a number of demographic and economic factors such as income, age distribution and the price of fuel. However, the information provided in this report shows the data at the market class level, and it is relatively easy to recompute the fleet fuel economy levels for any sales mix desired.

An example computation is shown to illustrate the derivation of the forecast. The example here is the Level I forecast for the large class to continue the example chosen for the baseline. First, the improvement in bsfc is calculated from the baseline. The factors are:

- Thermal efficiency improvement = 5.2 percent
- Pumping loss reduction = 45 percent
- Friction reduction = 20.5 percent

Of these, the friction reduction potential was adjusted to reflect the fact that the base vehicle had roller cam followers and low friction piston/rings. Hence:

$$\frac{bsfc}{bsfc_o} = \frac{1}{1.052} \quad \frac{(1 - 0.18 - 0.21)}{(1 - 0.18\ [1-0.8x0.45] - 0.21\ [1-0.67x0.205])}$$

$$= \frac{1}{1.052} \times \frac{0.61}{0.7036}$$

$$= 0.824$$

This calculation indicates that average bsfc over the cycle will decrease by 17.6 percent largely due to pumping and friction loss reduction. At risk Level I, weight is reduced by 18 percent through material substitution and 5

percent through packaging improvements, C_D is reduced by 36 percent, and C_R by 15 percent. The net energy requirement reduction is given by:

$$\frac{\Delta E}{E} = 0.54 \times 0.23 + 0.23 \times 0.36 + 0.25 \times 0.15$$

$$= 0.2391$$

Hence, $$\frac{FC}{FC_o} = 0.9 \times 0.824 \times (1-0.2391) + 0.1 \times 0.824$$

$$= 0.6467$$

The new fuel economy is simply 25.8/0.6467 or 39.9 MPG; in general, larger cars can have larger percentage improvements in fuel economy due to the packaging benefit and frontal area reduction potential relative to smaller cars.

In the Level II forecast, both diesel and gasoline vehicle fuel economy are estimated and then combined for an integrated market class average. As an example, the calculation for the subcompact class is shown. For gasoline engines, the bsfc improvement is estimated from

- Thermal efficiency improvement 6.87 percent
- Pumping loss reduction 66 percent
- Friction reduction 20.5 percent

Using the same equations, we obtain $bsfc/bsfc_o$ as 0.778. For the turbocharged diesel, $bsfc/bsfc_o$ is set to 0.690 from the assumed 45 percent increase in fuel economy over the baseline.

At risk Level II, weight is reduced through material substitution by 25 percent, and by 4 percent through improved packaging. The drag co-efficient is reduced by 46 percent, and frontal area by 1 percent. Tire rolling

resistance is reduced by 25 percent by 32.7 percent. Hence, it can be calculated that:

FC/FC_0 = 0.549 for gasoline engines
= 0.487 for diesel engines

The two estimates are weighted to reflect the 20 percent assumed penetration for diesels, and the 2010 fuel economy level is estimated at 63.37 MPG.

At risk Level III, all vehicles are assumed to use turbocharged D.I. diesels in conjunction with a hybrid storage devices as described for the VW Golf. Such a system is estimated to provide a 33 to 35 percent benefit in fuel economy, or a 25 percent reduction in bsfc, over an equivalent 2010 gasoline engine.

The results of the detailed forecasts of fuel economy by market class are shown in Table 5-3. The variation in improvements possible across market classes is small because of the technologically homogenous "baseline" used for 2001 as a maximum technology case. The numbers, although shown to an accuracy of one-tenth of an MPG, should <u>not</u> be taken to suggest that fuel economy in 2001 can be predicted to that level of accuracy. Rather, the results should be interpreted as follows:

- Even under a low risk assumption, it appears that the fleet can continue to improve from a little above 38 MPG (import and domestic) in 2001 to 45 MPG in 2010, without any major change in vehicle consumer attributes. The technologies that can be utilized to meet these levels are considered to not require any major breakthroughs in development.

- Under a higher level of risk, it may be possible to attain a fleet fuel economy level of about 55 MPG without any loss of consumer attributes. The technologies utilized to obtain these levels require significant advances from the current levels to meet regulatory requirements, but are unlikely to impact customer perceived attributes in any major way.

TABLE 5-3

FLEET FUEL ECONOMY IN
2010 AT DIFFERENT RISK LEVELS

Class	Mix*	Risk Level I	Risk Level II	Risk Level III**
Minicompact	3.3	68.5	83.4	110.0
Subcompact	26.5	51.5	63.4	86.6
Sports	7.3	39.7	47.8	68.9
Compact	23.2	46.4	57.0	74.0
Intermediate	22.4	42.2	51.3	69.7
Large	6.1	39.9	48.6	65.8
Luxury	11.2	37.2	46.2	62.1
Fleet	(100)	44.8	54.9	74.1

Note: This table assumes no new emission standards are legislated in the post-2000 time frame. Additionally, the table holds vehicle attributes constant at 1988 levels, except for Risk Level III.

* Unchanged from 2001 estimate.

** Based on (fossil fuel + fossil equivalent) MPG.

- A fleet average of about 75 MPG is possible if an energy storage device such as the electric hybrid becomes practical and the entire fleet is powered by small displacement, turbocharged direct-injection diesels. The former has problems associated with cost and consumer acceptability, while the latter has problems in meeting regulatory requirements and (possibly) winning consumer acceptance. Nevertheless, both technologies could well be feasible for widespread use by 2010.

5.3 COMPARISON OF FORECASTS TO PROTOTYPE FUEL ECONOMY

Although the individual technology effects were carefully documented in Section 4, the incorporation of all of the technologies on a single vehicle and the resulting fuel economy forecast needs to be documented. Of course, no car in production today has incorporated all of the technologies embodied in the forecast, and a validation of the forecast must rely on a few prototypes that utilize many of the technologies. Of course, these prototypes do not meet safety and emission standards, but the potential influence of such standards on fuel economy can be estimated separately.

To date, only subcompact sized prototypes have been built to meet goals of high fuel economy. Large car prototypes, though shown to the public, have not been accompanied by detailed data on weight, engine type and fuel economy. Accordingly, available comparisons to the forecasts are largely restricted to the subcompact/minicompact class of cars.

Volkswagen has presented a range of cars including the auto 2000 in 1983, the IRVW Futura in 1989 and the Golf Electric hybrid in 1986. The earliest one the Auto 2000 had characteristics approximately consistent with the estimated Level I characteristics. It had a drag co-efficient of 0.25 and a weight of 1765 lb, and tire rolling resistance that was "10 percent lower than conventional tires". However, the engine was a conventional OHC/3-cylinder gasoline engine fitted with a supercharger, and it had a four-speed automatic transmission. The resulting fuel economy on the EPA cycle was about 46 mpg, based on conversion from the ECE fuel economy test. Level I risk based estimates are 1890 lb weight, 0.24 C_D and a fuel economy of 51.5 MPG. The

major technology difference between the Level I and VW vehicle is the engine in the Level I forecast is a 5-valve cylinder, low friction design.

Table 5-4 provides data on some advanced prototypes shown in the mid-1980's. The Toyota AXV is somewhat larger than the minicompacts in the EEA forecast, and is between the mini and sub-compact classes modelled. The AXV attains a composite fuel economy of over 90 MPG as compared to the EEA prediction of 89.5 MPG for a minicompact, suggesting that EEA's forecast is conservative. However, the addition of a particulate trap or catalyst to meet emission standard, and weight increases to meet the safety standards may bring down the AXV's fuel economy to the 80 MPG range, consistent with the forecast. The Volvo LCP is closely representative of a subcompact and its combined fuel economy rating of 65 mpg is slightly lower than the 69.8 MPG forecast, consistent with its higher drag co-efficient and higher power to weight ratio.

The VW Golf electric hybrid is unique as its body and tires are not improved from current vehicles. VW provided emissions data on the production diesel Golf and the comparable electric hybrid prototype. They are:

	Production Golf	Hybrid Golf
HC	0.29 g/mi	0.25 g/mi
CO	1.45 g/mi	0.65 g/mi
NO_x	1.52 g/mi	0.40 g/mi
Particulate	0.26 g/mi	0.13 g/mi
Fuel Economy (City)	37.4 MPG	60 MPG diesel + electric equivalent

Highway fuel economy was not available but is expected to be similar to that of the production Golf or slightly lower (due to increased weight), since the electric motor is not used at speeds above 20 mph. Hence, it is estimated that a highway fuel economy of 50 MPG will result will result in a composite

TABLE 5-4

CHARACTERISTICS OF HIGH FUEL ECONOMY

PROTOTYPES

	Hybrid VW Golf	Toyota AXV	Volvo LCP
Weight (lb)	2450	1430	1560
C_D	0.34-0.36	0.26	0.25-0.28
Engine Type	1.6 liter 4-cyl I.D.I. Diesel	1.1 liter 3-cyl D.I. Diesel	1.4 liter 3-cyl D.I. Diesel
Horsepower	52	56	90
Power boost	(6 kw Electric Motor)	Turbo	Turbo (intercooled)
Transmission	Hybrid electric + 4-speed manual	CVT	5-sp. manual
Air-Conditioner	N/A	New high efficiency unit	N/A
Fuel economy - city	~ 60 mpg (equivalent)	~ 80 mpg*	56
highway	---	~110 mpg*	81
Acceleration time (0-60)	~16	12 (est.)	~10
Seating capacity	4	4	2 + 2 rear facing

* Calculated from Japan 10-mode/60 km-hr values, or ECE cycle values.

fuel economy of 55 MPG, which is about 33 percent higher than the production Golf. These figures are consistent with the hybrid vehicle's fuel economy. It should also be noted that the vehicle meets the 0.4 g/mi NO_x standard and applicable safety standards.

No large and intermediate size high fuel efficiency prototype data is publicly available, but the scaling laws relating the fuel consumption of small cars to large cars show that the fuel economy ratios are comparable to those observed today. Based on these necessarily limited comparisons, it can be concluded that the EEA forecasts are probably within ±5 percent of the attainable values for specific sets of technologies in 2010.

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